Harvesting Nature's Potential: Botanical Biomass for Unprecedented Sustainable Energy Solutions

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Abstract

Botanical biomass is a diverse spectrum of organic materials derived from plants and agricultural residues. It is recognized as a renewable and low-carbon alternative to conventional fossil fuels. Bioenergy is an upcoming sector that incorporates efficient utilization of these renewable energy sources globally and will be a deciding factor in meeting future energy goals. In the current scenario, wherein other renewable energy sources may not be the most potential ones, as they suffer from intermittency, and do not currently offer the necessary heat intensity; bioenergy can surely serve as the ideal solution. This is also a much-needed thread toward achieving climate-compatible futuristic energy demands. The fossil fuel industry is hard to compete with the present global energy demands, and therefore enduring, resilient, and highly efficient energy sources must be embraced.

This chapter serves as a comprehensive review of the types and sources, industrial processing, applications, and pioneering advancements that have played a crucial role in unlocking the immense potential of botanical biomass for energy harvesting and storage. The employment of bioenergy is reinforced through compelling case studies and real-world examples, which underscore their economic viability and commendable environmental sustainability. In conclusion, this segment envisions a transformative energy revolution facilitated by the harmonious collaboration between botanical biomass and the environment. Embracing this holistic approach holds the key to cultivating an unparalleled sustainable energy landscape, effectively mitigating climate change impacts, and securing a pristine future generation to come.

Keywords: Botanical biomass, bioenergy, environmental sustainability, climate-compatible energy

Introduction

With the ever-escalating demands for fuel due to the population explosion and urbanization, the influx of diverse energy sources is also increasing. The conventional sources of energy are fossil fuels such as coal, crude oil, and natural gas, and they still remain the most utilized sources because of the convenience associated with their usage but, the coexisting predicaments cannot be overlooked. The world today is distraught with the increasing environmental and health hazards because of the harmful by-products that are released into the environment by fossil fuel burning, for e.g. carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen dioxide (NO_x), nitric oxide (N_2O), volatile organic compounds (VOCs), and hydrocarbons (HCS). The methods of fossil fuel extraction are also degrading the environment at a frightening pace. It has led to serious concerns, such as emissions of greenhouse gases, land degradation, water pollution, ocean acidification, global warming, habitat fragmentation, declining fossil fuel reserves, etc. As the world continues to grapple with these challenges it is imperative to transit towards cleaner and greener energy resources, which would pave the way towards sustainable energy.

Fortunately, we are not locked in a fossil fuel future and great progress has been made in finding and scaling up of environmentally harmonious renewable alternatives to generate energy. These renewable sources include wind, hydro, geothermal, solar, tidal and biomass energy (bioenergy) etc. Bioenergy is derived from fixed organic matter in plant and animal sources such as dedicated energy crops, agricultural crop residues, forestry residues, algae, wood processing residues, municipal waste, and wet waste. Around three-quarters of the world's renewable energy comes from bioenergy and more than half of it is traditional bioenergy (www.irena.org). Traditional bioenergy includes the combustion of biomass such as wood, animal waste, and traditional charcoal straightaway, whereas modern bioenergy includes liquid biofuels produced from bagasse and other plants; bio-refineries; biogas produced through anaerobic digestion of residues; wood pellet heating systems; and other technologies. Traditional bioenergy is mostly practiced in underdeveloped and developing while modern bioenergy considering the cost and expertise involved is being established in developing and developed countries as well. Bioenergy derived from these sources could be utilized as biogas, bioethanol, and biodiesel. As we venture into the future, technological evolution, heightened environmental awareness, and the compulsion to achieve sustainable development goals are converging to shape the trajectory of this green and clean energy resource.

The biomass ingests the sun's energy in the developmental phase and discharges it during the ignition phase. So, theoretically, the bioenergy derived from the biomass is carbon-neutral. However, few reports also suggest otherwise (Ahamer, 2022). From ancient civilizations, use of wood for heat and cooking to the more recent advancements in biofuel production, the evolution of biomass energy has been a testament to human ingenuity. Considering the current scenario, the organic materials that could be used to produce biomass are countless since our societies; rural as well as urban, consistently produce waste such as garbage, wood, faeces, and agricultural waste. The decaying of dying animals and plants also adds a huge amount naturally. Bioenergy is therefore also seen as a way to dispose of organic waste. Hypothetically, biomass asserts a limitless supply and encourages industrial symbiosis which ascribes its pivotal role in steering us towards a more harmonious coexistence with our planet's delicate ecosystems.

Global Bioenergy Share and Policy Frameworks

Globally, in 2020, the traditional use of biomass for cooking and heating accounted for the largest share (54 %) followed by heat in the industry (21%), heat in buildings (12%), transport (7%) and electricity (6%) (Statista, 2023). Appreciating the rise in the generation and consumption of biomass-derived energy, the future is set to unfold its immense potential in various energy-demanding sectors. In the total primary energy supply, fossil fuels account for 81 %, nuclear energy represents 5 % and renewable energy sources 14 % (of which the contribution of biomass is about 70 %) (Renewables, 2018). The share of renewable energy is increasing and has reached to approx. 30 % in 2021 (Statista, 2023). In 2022, China, US, Brazil, India and Germany are the leading countries in installed renewable energy capacity worldwide (Statista, 2023). Biomass-derived energy is the biggest renewable energy source globally and accounts for nearly 55% of the renewable energy and 6 % of the global energy supply (IEA (2023). The global production of bioenergy in 2021 was 614 gigawatts which was almost double the production in 2011 (Statista, 2023). In India, renewables made up 22% of the total energy supply in India in 2019. In 2021, the renewable energy share in final energy consumption increased up to 31% (of which the contribution of biomass is 85%) (IEA, 2021).

The bioenergy capacity of India has increased from 3,929 megawatts (in 2012) to 10, 670 megawatts (in 2022) in the last ten years (Statista, 2023).

The policy frameworks and international collaborations play a significant role in laying the foundations for the establishment of bioenergy mileposts. One such International treaty is the Paris Agreement which targets of net-zero GHGs emissions to combat climate change. New policies are being implemented for the successful adoption of green energy in various energy-demanding sectors. Globally, these policies compel various industries to make use of some definite share or more to be sourced from bioenergy. For example, in India, the biomass policy mandates 5% biomass co-firing in Thermal Power Plants (TPPs) from 2024-2025, which shall increase to 7% from 2025-26 (Ministry of Power, 2023). All over the world, countries are working in collaboration to accomplish the goal of restricting climate change by limiting the global temperature rise by 1.5 degrees till 2025, and since biomass-derived energy is almost carbon-neutral, it may prove a cornerstone in sustainable future energy.

This chapter embarks on the innovative dimensions of biomass energy, unveiling futuristic trends that would reshape the energy industry. It emphasizes on the importance of bioenergy and its placement amongst various energy sources, through a comprehensive analysis of the technologies, challenges, advantages, policy frameworks, and futuristic approaches. Furthermore, the chapter explores the symbiotic relationship between biomass energy and other sustainable practices, such as carbon capture and waste management, and agroforestry, propelling the concept of holistic environmental sustainability to the forefront.

Botanical Biomass: Importance and challenges

The energy landscape is composed of various types and sources of botanical biomass that contribute to the greening of energy production. Using plants, algae, and other biological materials as a sustainable source of energy is referred to as using botanical biomass. Agricultural waste, food waste, energy crops, grasses, algae, anaerobic digestion plant waste, and sewage sludge are some of the sources of botanical biomass. Biomass from plants is a type of solar energy that has been captured. Due to its carbon neutrality and low sulphur content in comparison to fuels obtained from fossil sources, this form of energy is seen as being environmentally friendly.

The benefits of using botanical biomass as a cleaner fuel source for electricity generation are numerous. Since biomass fuels emit less CO_2 than fossil fuels do, it lowers greenhouse gas emissions. Additionally, the CO_2 emissions from using biomass can be successfully sequestered, lowering the environmental impact even more. This means that the CO_2 emissions from the usage of biomass can be captured and stored, further reducing its environmental impact (Keith et al., 2009). Renewable energy is another key benefit of using botanical biomass as energy. Natural processes like photosynthesis can renew the live organisms that make up botanical biomass. This guarantees a steady and sustainable supply of biomass for the production of energy. Additionally, growing biomass crops can improve soil carbon sequestration and offer extra ecosystem services, which helps to maintain a healthy carbon balance (Lal, 2005). This dual function of plant biomass in reducing emissions and storing carbon highlights its significance in combating climate change.

Challenges

Amidst the challenges posed by climate change, biomass-derived energy can contribute significantly towards GHG mitigation and provide diversification of various energy sources, which would ultimately reduce the pressure on primary energy sources and other renewable sources. An average of 25 % of the primary energy can sustainably be sourced from bioenergy. It becomes our moral duty to develop and supply large-scale bioenergy in ways that improve social development that could encourage a significant downturn in fossil carbon emissions. Although the prominence of bioenergy is being established globally, but its slow pace is a matter of concern. Expansion of infrastructure for successful installation of modern bioenergy set-ups is also in the inception stage in many underdeveloped and developing countries and would need a substantial amount of time. The development of infrastructure for production, collection, and processing along with transmission and storage, also needs a meticulous array.

Competition for land and resources is one major issue, particularly when biomass production competes with food crops or natural ecosystems. To avoid negative effects on food security and biodiversity, sustainable land-use planning and policy are required (Searchinger et al., 2008). Aside from that, modern infrastructure and technologies are needed for the efficient conversion of plant biomass into bioenergy or biobased goods, which could provide financial and logistical difficulties. A crucial part of shifting to a more bio-based and sustainable economy is ensuring the sustainable supply and effective exploitation of botanical biomass while addressing these issues.

The Importance of Botanical Biomass

In the perspective of preventing climate change and attaining sustainability, the significance of greening the energy landscape cannot be emphasized. The main energy sources in the past have been fossil fuels like coal, oil, and natural gas, which have greatly increased greenhouse gas emissions and caused global warming. It is essential to switch to renewable energy sources, like solar, wind, hydroelectric, and geothermal energy, in order to lower carbon emissions and mitigate the negative consequences of climate change. A study by Davis *et al*., (2018) estimates that replacing fossil fuels with renewable energy sources could reduce global carbon dioxide emissions by up to 80% by 2050, a substantial step towards limiting global warming.

Beyond carbon reduction, there are various more benefits associated with greening the energy sector. By reducing reliance on imported fossil fuels, switching to cleaner energy sources can increase energy security while also lowering health risks linked with air pollution and improving the quality of air and water. A thorough research (Jacobson *et al*., 2015) emphasizes that switching to only clean, renewable energy systems can have a significant positive impact on both health and the economy. Therefore, greening the energy sector is not just a necessity for the environment but also a means of ensuring that mankind has a more robust, healthy, and sustainable future.

Bioethanol is one kind of plant biomass in particular that has drawn a lot of interest. A renewable energy source known as bioethanol is created by fermenting plant materials like corn and sugar cane. Research has revealed that producing bioethanol has many advantages over using fossil fuels. The complete amount of CO2 that is taken in from the environment during photosynthesis and that is released during biomass burning are both conserved during the creation of bioethanol.

Different Types of Botanical Biomass

Botanical biomass is composed of up an extensive range of plant-derived substances that have become increasingly significant in a number of industries, such as bioenergy, agriculture, and biorefining. Based on their origins and properties, many kinds of botanical biomass can be grouped.

Lignocellulosic biomass is rich in cellulose, hemicellulose, and lignin. Examples include wood, agricultural leftovers (such as maize stover, wheat straw), and crops grown specifically for energy (such as switchgrass). The main source of feedstock for the manufacture of biofuels is lignocellulosic biomass, which is seen as a sustainable substitute for fossil fuels. To maximize the energy potential of lignocellulosic biomass, researchers have investigated a variety of pretreatment and conversion strategies (Himmel *et al*., 2007). Lignocellulosic biomass is now an attractive option for the generation of bioethanol and biogas due to innovations in enzymatic and microbiological conversion processes (Sims *et al*., 2010). Numerous case studies show how botanical biomass is successfully used in a variety of applications, highlighting the potential of resources obtained from plants for accomplishing sustainability objectives. The use of lignocellulosic biomass in the creation of advanced biofuels is one notable example. It uses a sophisticated biochemical technique to create cellulosic ethanol from agricultural leftovers and energy crops. It has proven that it is possible to produce sustainable biofuels on a large scale from non-food biomass, which emits fewer greenhouse gases than conventional fossil fuels (Galbe & Zacchi, 2012).

Due to its great production and possible uses in biofuels, food, and medicine, algal biomass has drawn interest. In order to produce biofuels like biodiesel and biogas, algae, which are photosynthetic microorganisms, gather lipids and carbohydrates (Chisti, 2007). Algal biomass production is a viable source of sustainable biomass since it can be adjusted to certain strains and optimized for different environmental factors (Drosg, 2009). To improve algal biomass productivity and composition for different applications, researchers are still investigating genetic engineering and cultivation techniques (Stephens *et al*., 2010).

Lastly, woody biomass from trees and shrubs, such as willow and poplar, offers unique advantages due to its perennial nature and potential for carbon sequestration. Woody biomass has the potential to be transformed into high-value goods including bio-based chemicals and materials as well as biofuels (Jrgensen *et al*., 2017). Sustainable management and agroforestry techniques have been developed to maximize the production of woody biomass while enhancing ecosystem services (Nair *et al*., 2009). These methods not only supply biomass for numerous sectors but also help to preserve biodiversity and enhance soil.

Thus, for the sustainable generation of bioenergy and biorefining, several types of botanical biomass, such as lignocellulosic, algal, and woody biomass, constitute important resources.

The potential of these feedstocks for a variety of uses is constantly increasing because to developments in biomass conversion technology, agricultural techniques, and genetic engineering. This helps to accelerate the shift to a more environmentally friendly and bio-based economy.

The Future of Botanical Biomass in Renewable Energy

As the world looks for sustainable replacements for fossil fuels, the future of botanical biomass in renewable energy offers enormous promise. In order to decarbonize the energy sector, biomass-derived energy, such as biofuels, biogas, and biomass-based power, is positioned to be extremely important. The effectiveness and environmental sustainability of biomass consumption are constantly improving thanks to advanced conversion technologies including pyrolysis, gasification, and biochemical processes (Mohammad *et al*., 2020). Additionally, second-generation biofuel production from non-food feedstocks including lignocellulosic biomass and algae has picked up steam in response to worries about competition between food production and land use (Klein-Marcuschamer *et al*., 2012). The incorporation of plant biomass into renewable energy systems is anticipated to rise as research and innovation in the sector develop, lowering greenhouse gas emissions and improving energy security.

To effectively utilize the potential of botanical biomass in renewable energy, a number of issues must be solved. These include addressing land-use conflicts, maintaining a sustainable biomass supply, and addressing the economic sustainability of biomass-based electricity (Mabee *et al*., 2014). In order to reduce unfavourable effects, the environmental effects of biomass production and conversion processes must be properly handled. To ensure that biomass efficiently aids in the shift to a cleaner and more sustainable energy landscape, the future of botanical biomass in renewable energy will depend on a combination of regulatory support, technological improvements, and sustainable practices.

Biomass as eco-friendly energy source

Eco-friendly energy sources present a dual advantage, not only in their environmental impact but also in the profound benefits they bestow upon human health. Fossil fuels, notorious for their noxious emissions, contribute to a range of ailments, including respiratory diseases, cardiovascular disorders, and premature mortality. The World Health Organization (WHO) estimates that air pollution is responsible for a staggering 7 million deaths globally each year

(Kumar and Majid, 2020). In stark contrast, eco-friendly energy sources stand as a bulwark against this health crisis. Wind and solar energy, champions of clean energy, operate without emitting pollutants. However, it's biomass energy, often overshadowed, that provides a unique solution to deforestation. By utilizing organic matter for energy, we reduce the pressure on forests as a fuel source, thereby preserving crucial ecosystems. By embracing these sustainable alternatives, we not only decelerate air pollution but also safeguard human lives while mitigating deforestation (Kumar *et al*., 2023). The economic potential of eco-friendly energy sources is not just promising; it's revolutionary, poised to reshape industries and livelihoods. These sources don't just tap into natural power; they unlock a new horizon of job opportunities. According to the International Renewable Energy Agency (IRENA), renewable energy sectors employed approximately 11 million individuals globally in 2018. This surge in job creation spans various sectors, from manufacturing to installation, operation, maintenance, and research (JHU, 2021). Furthermore, the financial equation tilts favourably towards eco-friendly energy. Fossil fuels often mask their true cost by neglecting the externalities they impose, including environmental degradation and health consequences. This burden is shouldered by societies and future generations.

In an era marked by geopolitical uncertainties and energy dependence, the diversification offered by eco-friendly sources fosters energy security. Unlike fossil fuels that face supply disruptions and volatile prices, these renewable options present a reliable and abundant reservoir of energy (NRDC, 2018). Eco-friendly energy sources embody more than environmental and economic benefits; they champion social justice as well. The energy divide, exacerbated by nearly 800 million people lacking electricity access and over 2.8 billion relying on traditional biomass, reflects an inequity that needs addressing. This divide is most acutely felt in rural and underserved areas of developing nations (NRDC, 2018). Eco-friendly energy sources provide a path to redress this inequity. They offer decentralized and off-grid solutions, reaching far-flung communities that have long been marginalized. This not only empowers those at the fringes of society but also bridges the gap between the haves and have-nots. And in the context of biomass energy, it's important to note that its utilization can provide a double benefit: clean energy for communities and a reduced demand for wood fuel, thereby mitigating deforestation pressures.

Biomass energy is a type of renewable energy that comes from organic materials such as plants, animals, and waste. Biomass energy can be used to generate heat, electricity, or biofuels. Biomass energy has several advantages and disadvantages compared to other energy sources

(Mishra *et al*., 2018). It is widespread and plentiful in many parts of the world. As a result of fossil fuels being replaced, it can lower greenhouse gas emissions and air pollution. For farmers and rural communities, it can generate revenue and jobs. But biomass energy has some drawbacks, if not managed responsibly, it may result in deforestation and land degradation. During burning, it may release impurities such particulate matter, nitrogen oxides, and carbon monoxide. For the growth of crops, it can use a lot of water and fertiliser. Compared to other renewable energy sources, it may have a low energy efficiency and a high cost. It may compete for resources and land with food production and biodiversity.

There are numerous ways to generate biomass energy. Most frequently source derived from wood for the production of energy from biomass. It can be immediately burned to provide heat or transformed into energy or biofuels. Plantations, forests, and wood residues from businesses and homes are all sources of wood. Plants like corn, sugarcane, soybeans, rapeseed, sunflowers etc. raised expressly for harvesting energy can be transformed into biofuels like ethanol and biodiesel. Organic material that is abandoned or undesirable like sewage sludge, animal waste, agricultural waste and municipal solid trash after anaerobic digestion or incineration can be utilised to generate biogas or power from it.

Biomass energy is considered a clean energy source because it is based on organic characteristics, resulting in minimum harmful emissions that will be discharged (Wang *et al*., 2022). Utilizing biomass waste and their ashes along with mineralized CO_2 may help close the "loop" in the "emission-capture" process while also offering a sustainable management path for leftovers that have negative environmental effects. (Tripathi *et al*., 2020). However, biomass resources like plants and forests must be managed sustainably if the earth is to properly maintain the carbon cycle process. Reabsorbing and sequestering carbon in trees and other plants, like switchgrass, takes decades. The process may be severely hampered by uprooting or soil disturbance. A healthy environment requires a consistent and diverse supply of trees, crops, and other plants.

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