Bioenergy- a sustainable and reliable source for clean energy

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Abstract

The 21st century is fraught with dangers like environment pollution and climate change. These problems should be of great concern not only because of nature's intrinsic value but also because of ethical concerns for future generations. Hence, there is a dire need for a novel sustainable strategy for the production of bioenergy which can make significant contributions in reducing carbon emissions, especially from difficult-to-decarbonize sectors like aviation, heavy transport, manufacturing etc. Worrisome rise in our reliance on fossil fuels like oil, coal and natural gas has led to depletion of these resources thereby further aggravating the scenario. Globally finding ways to facilitate this shift is difficult, and thus more policy initiatives are being tested using models before their execution in practice.

Bioenergy technology, a sustainable and reliable technology is emerging as a potential strategy/ process for energy requirements. The creation of energy (electrical, thermal, chemical and acoustic) by biological processes that affect both living and non-living systems is featured as bioenergy that can be the answer to be sought. Many nations' decarbonization programmes are a part of the transition to renewable and low-carbon energy sources. As a result of their ability to address issues with energy security and environmental pollution, bioenergy systems are anticipated to grow during the ensuing decades. The main renewable energy sources include biogas, bioethanol, coal, hydrogen and biodiesel. Recent developments in data science and machine learning (ML) can provide new opportunities. The latest advances in ML assisted bioenergy technology, including energy utilization of lignocellulosic biomass, microalgae cultivation, biofuels conversion and their applications. In addition, microbes provide a platform for the synthesis of clean energy from renewable resources. Significant investments in discovering new microbial systems and capabilities, discerning the molecular mechanisms that mediate microbial bioenergy production, and optimizing existing microbial bioenergy systems have been made.

Any renewable energy project, however, can only be permitted if it is certified for being more environmentally superior than its conventional competitors.

Keywords: Bioenergy, Biomass energy, Sustainable strategy, Renewable energy

Background

From the North Pole to the South Pole, the earth is warming up. Our planet's climatic conditions and environment are being affected by a complicated shift brought on by the population growth, urbanisation, and industrial revolution. The average surface temperature has risen more than 1.6 degrees Fahrenheit globally since 1906 (0.9 degrees Celsius)(1). And the repercussions of rising temperatures are already being felt; they are not something that will happen in the far future. This puts both ourselves and all other kinds of life on Earth in grave danger. In 2021, four important markers of climate change—greenhouse gas concentrations, sea level rise, ocean heat content, and ocean acidification—have reached their worst states. This is another unmistakable indication that human activities are having substantial and long-lasting effects on planetary-scale changes in the land, the ocean, and the atmosphere. Therefore, ending our dependence on energy produced from fossil fuels and moving to sustainable and renewable energy sources has now become essential for solving this crisis (2).

Today, fossil fuels are the main source to meet energy needs. However, there are two major ways by which fossil fuels harm our ecosystem. First, burning fossil fuels causes massive emissions of greenhouse gases like carbon dioxide (CO_2) into the atmosphere. Second, extraction of fossil energy results in the annual release of enormous amounts of greenhouse gases along with oil spillage, deforestation and habitat destruction, water pollution etc. Moreover, long-term use of fossil fuels is also time-limited because they are not renewable. According to a report in 2020, 84% of the global energy consumption is still obtained from fossil fuels (BP Stats Review of World Energy 2020).

One of the biggest issues that humanity will confront in the future decades is the availability of sustainable energy, especially in light of the need to combat climate change. The sustainable provision of future energy demand can be significantly aided by biomass. It is currently the largest global contributor of renewable energy in the world and has a lot of room to grow in terms of producing heat, power, and transportation fuels. By replacing imported fossil fuels with domestic biomass, further bioenergy deployment, if carefully managed, could improve energy security and trade balances, contribute even more to the world's primary energy supply, significantly reduce greenhouse gas emissions, and potentially have other positive environmental effects. It could also provide opportunities for rural communities to develop economically and socially and provide waste disposal options. An overview of the potential for bioenergy and the difficulties posed by its expanded use is given in this review. In relation to resources, technology, practices, markets, and policy, it addresses opportunities and hazards. The objective is to offer insights into the possibilities and steps needed to build a sustainable bioenergy business.

1. What is bioenergy?

Burning biomass fuel generates bioenergy, a form of renewable energy. A variety of organic materials, including harvest leftovers, carefully bred crops, and organic waste from our homes, workplaces, and farms, can be used to make biomass fuels. When used as an energy source, biomass is referred to as "feedstock." Feedstocks can be made from waste materials from industries including agriculture, food processing, and wood production, or they can be produced specifically for their energy content (an energy crop). Dry, flammable feedstocks, like woody biomass, are burned in boilers or furnaces. This results in the water boiling, creating steam, and moving a turbine to generate electricity. Food waste and other wet feedstocks are put in sealed tanks where they rot and release methane gas (also called biogas). Energy can be produced using the generated gas. As an alternative, it can be used for heating and cooking by being supplied into the national gas infrastructure. Solar energy from photosynthesis or the metabolic activity of living things is converted into biomass energy, which is then stored in the chemical bonds of carbon and hydrogen chains. As a result of its capacity to store energy until needed, which makes it more reliable and responsive than the sun or wind energy, biomass is sometimes referred to as nature's solar battery.

Since the dawn of civilization until the industrial revolution, biomass has been the main source of energy used by humans for heating and cooking. The world's primary energy mix consists of about 10% biomass, the most majority of which is derived from wood. This makes biomass the most widely used renewable energy source. The production of heat, power, and transportation fuels from biomass has recently attracted considerable attention. As a way to diversify their agricultural industries, many nations have implemented measures to boost bioenergy. Potentially abundant biomass resources exist around the world, and both industrialised and developing nations have the opportunity to utilise it more frequently (3).

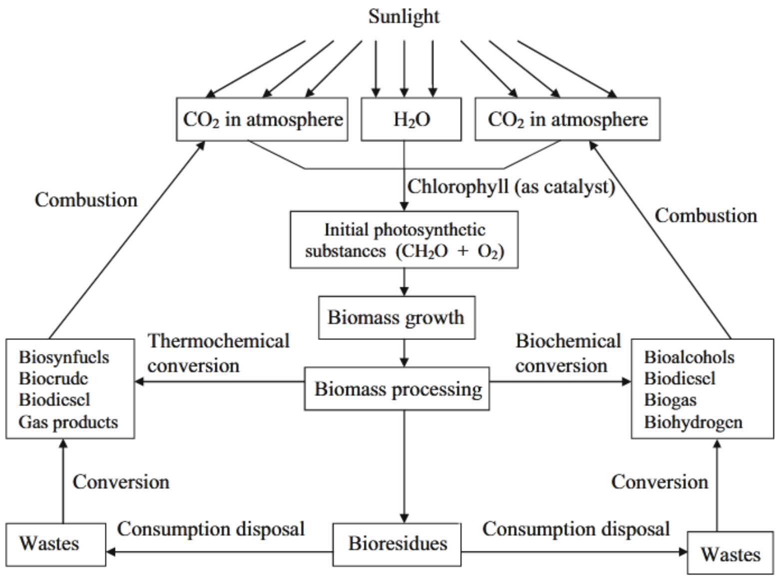

Figure 1: Carbon cycle, photosynthesis, and main steps of biomass technologies
Siedlecki, M., De Jong, W., & Verkooijen, A. H. (2011). Fluidized bed gasification as a mature and reliable technology for the production of bio-syngas and applied in the production of liquid transportation fuels—a review. *Energies*, *4*(3), 389-434.

2. Biomass as bioenergy resources and It's potential

As per reports, on December 2020 human-made materials have outweighed Earth's entire biomass (17). Biomass is an organic resource that comes from both plants and animals and is clean and renewable. It stores chemical energy produced by the sun. Since plant or algal biomass gets its initial energy from the sun, it can renew swiftly. Trees, crops, and municipal solid waste are all easily accessible and can be carefully managed. In many countries, particularly in less developed ones, cooking and heating with biomass is a common practice. The use of biomass fuels for electricity generation and transportation is expanding in many industrialised countries as a means of reducing carbon dioxide emissions from burning fossil fuels. Although processing biomass into a range of sustainable liquid and gaseous fuels is another possibility, direct combustion of biomass for heating is one of those.
Biomass sources for energy include:

- Wood and wood processing wastes - firewood, wood pellets, and wood chips, lumber and furniture mill sawdust and waste, and black liquor from pulp and paper mills.
- Agricultural crops and waste materials - corn, soybeans, sugar cane, switchgrass, woody plants, and algae, and crop and food processing residues, mostly to produce biofuels.
- Biogenic materials in municipal solid waste - paper, cotton, and wool products, and food, yard, and wood wastes.
- Animal manure and human sewage for producing biogas/renewable natural gas.

Biomass has been used ever since people began using it to heat their homes and cook their food. Wood is still the most prevalent biomass energy source in the market today. Additional sources include food crops, grassy and woody plants, agricultural or forestry wastes, oil-rich algae, and the organic fraction of municipal and industrial wastes. It is possible to utilise biomass energy from landfill emissions, which are mostly made of methane, the main gas in natural gas. It can be used as an alternative for the fossil fuels that are generally used to produce fuel, power, and other products. Technology for biorefineries is being developed to convert biomass into a range of valuable fuels, chemicals, materials, and products, just like oil refineries and petrochemical facilities do.

Bioenergy Technologies

Biofuels: To address the needs of transportation, biomass is transformed into liquid fuels, such as ethanol and biodiesel, known as biofuels. Unlike other renewable energy sources, biomass has the potential to be immediately converted into liquid fuels to help with the demand for transportation fuel. Ethanol and biodiesel are now the two most widely used types of biofuels. Like beer and wine, ethanol is a form of alcoholic beverage (although ethanol used as a fuel is modified to make it undrinkable). It's commonly made by fermenting any biomass that contains a lot of carbohydrates in a manner analogous to brewing beer. The main use of ethanol is as a gasoline addition to increase octane and lower pollutants that contribute to pollution, such as carbon monoxide. Some automobiles, referred to as Flexible Fuel Vehicles, are made to operate on E85, an alternative fuel that includes a significant amount more ethanol than regular gasoline. Alcohol (usually methanol) and vegetable oil, animal fat, or used cooking grease are combined to produce biodiesel. In its purest form, it is utilised as a renewable alternative fuel for diesel engines or as an additive (often 20%) to reduce vehicle emissions.These bacteria use the sun's energy to mix carbon dioxide with water, resulting in biomass that is more efficient and faster than that of terrestrial plants. Oil-rich microalgae strains are capable of producing the raw materials for a range of transportation fuels, such as biodiesel, "green" diesel and gasoline, and jet fuel, while minimising the consequences of carbon dioxide emissions from sources like power plants.

Biopower: Renewable biomass fuels are converted into heat and electricity via one of three processes in biopower systems: burning, bacterial breakdown, or conversion to gas or liquid fuel. In order to reduce its emissions of greenhouse gases, India has committed to increasing its use of renewable energy. By 2030, the nation's long-term plan calls for the installation of 450 GW of renewable energy. By balancing the seasonal and hourly power demands that intermittent renewables might not be able to meet, bioenergy can play a crucial role in the energy balance (4). Numerous obstacles must be overcome for the development of cellulosic feedstock-based bioenergy industries. These include the need for processing technology developments and evidence of environmental advantages. Also, How will suppliers of raw materials and processors interact? Which supply mechanisms will they employ? Will long-term agreements or vertical integration win out? Will biomass spot markets emerge? Will the costs of maintaining these linkages be kept low enough that the technologies can be implemented? (5) However, the organisation of biomass-based firms continues to be a non-technical challenge.

Bioproducts: Biomass can be transformed into chemicals for the production of plastics and other goods that are traditionally made from petroleum in addition to energy and fuels. Potential markets for bioproducts such polymers, lubricants, solvents, adhesives, herbicides, and medications are diverse and sizable. Many first-generation biomass-derived bioproducts are currently being viewed with caution since they:

- unless the biomass feedstock is generated responsibly, do not achieve their claimed environmental benefits;
- are negatively impacting indirect land-use change (ILUC), including speeding deforestation;
- have a potentially negative impact on biodiversity;
- give expensive, insufficient GHG reduction benefits (apart from sugar cane ethanol);
- are an expensive option for improving energy security; and
- contribute to higher food prices (16).

Benefits of Biomass

Biomass can provide an array of benefits.

- Renewable Energy Source: Biomass is a renewable energy source when managed sustainably because it is derived from living organisms that can be replanted, regrown, or replenished. The cyclical nature of biomass growth, harvest, and carbon exchange with the atmosphere allows it to provide a consistent energy supply while minimizing its impact on greenhouse gas emissions. This renewable characteristic of biomass makes it an important component of the transition to more sustainable and environmentally friendly energy systems (55).
- Reduced Greenhouse Gas Emissions: Biomass-based bioenergy technologies release fewer greenhouse gases, particularly carbon dioxide (CO_2), compared to fossil fuels. The carbon emitted during combustion is offset by the carbon absorbed by plants during growth, making it a carbon-neutral energy source (54).
- Waste Reduction: Agricultural residues, forestry byproducts, and organic municipal waste can be utilized for bioenergy production, reducing waste disposal and providing income for farmers. By converting byproducts into valuable bioenergy resources, reducing landfill waste, and reducing landfill waste, these methods help mitigate environmental issues and enhance resource efficiency, aligning with the principles of a circular economy (53).

- Biomass Residues: Agricultural and forestry residues can be converted into biomass for bioenergy, reducing waste and pollution. This practice maximizes the utility of cultivated land, promotes sustainable biomass supply, and contributes to responsible forest management practices. Additionally, agricultural residues can be sold for bioenergy production, diversifying revenue streams and increasing economic sustainability. Both residues are carbon-neutral or carbon-negative feedstocks, reducing net carbon emissions (56).
- Technological Advancements: Ongoing research and development in bioenergy technologies have led to improved efficiency, reduced emissions, and increased energy yields, making biomass-based bioenergy more competitive and sustainable (53).
- Greenhouse Gas Emissions Reduction: By employing biomass energy, greenhouse gas emissions can be greatly reduced. Burning biomass releases about the same amount of carbon dioxide as burning fossil fuels. Fossil fuels, on the other hand, release carbon dioxide, which is essentially a "new" greenhouse gas that was originally held in check by photosynthesis millions of years ago. But the carbon dioxide that biomass releases is largely offset by the carbon dioxide that it absorbs during its own growth (depending how much energy was used to grow, harvest, and process the fuel). Studies have shown that harvesting trees for biomass results in a carbon penalty that takes decades to recover from, hence it is preferable for biomass to be cultivated on previously cleared land, such as unused farmland (6).
- Foreign Oil Dependence Reduction: Due to the fact that biofuels are the only renewable liquid transportation fuels available, using biomass can minimise reliance on foreign oil. The agriculture and forest products sectors are supported by biomass energy. Municipal garbage, scrap from lumber mills, and paper mill leftovers are the principal biomass feedstocks for energy. The most widely utilised feedstocks for biomass fuels today are soybeans and maize grain (for ethanol production) (for biodiesel). Agri-residues including wheat straw and maize stover (the plant's stalks, leaves, and husks) will also be used in the near future, thanks to technology created by NREL (National Renewable Energy Laboratory). Algae and fast-growing trees and grasses are only a couple of the devoted energy crops that will be grown and used in the long run. On areas that won't support intensive food crops, these feedstocks can be grown sustainably (6).

How much biomass is used for energy?

About 4.8 quadrillion Btu, or 4,835 trillion British thermal units (TBtu), or 5% of the United States' total primary energy consumption, came from biomass in 2021. About 2,316 TBtu of the total came from biofuels (mostly ethanol), 2,087 TBtu from wood and biomass derived from wood, and 431 TBtu from biomass found in municipal solid waste and sewage, animal manure, and agricultural leftovers (14,15).

The amounts—in TBtu—and percentage shares of total U.S. biomass energy use by consuming sector in 2021 were:

(U.S. Energy and Information Administration)

Sector	Consumption of energy	Percentage
Industrial	2,313 TBtu	48%
Transportation	1,477 TBtu	31%
Residential	464 TBtu	10%
Electric power	435 TBtu	9%
Commercial	147 TBtu	3%

Both in terms of energy content and percentage of overall annual U.S. biomass consumption, the industrial and transportation sectors dominate (U.S. Energy and Information Administration). Biomass is used in combined heat and power plants by the paper and wood products industries to produce energy for internal consumption as well as process heat. The majority of the biomass used in the transportation sector is for liquid biofuels (U.S. Energy and Information Administration).

Firewood and wood pellets are used for heating in both the household and commercial sectors. Additionally, the business sector uses and occasionally sells renewable natural gas created by municipal sewage treatment plants and landfills for trash (U.S. Energy and Information Administration).

Wastes created from biomass, such as wood, are used by the electric power sector to produce electricity that is sold to other industries (U.S. Energy and Information Administration) (14,15).

3. How to convert biomass into bioenergy ?

Biomass is a one-of-a-kind renewable resource in many aspects. It is relatively easy to store and transport, in contrast to renewable sources such as wind and solar, which provide intermittent electrical power that requires immediate use and grid connection.The cost of biomass frequently makes up a sizable amount (usually in the range of 50–90%) of the cost of producing bioenergy because waste and residues are not present.This sets the economics of bioenergy apart from those of other renewable energy options, which mostly rely on unpaid resources (e.g. wind, sunlight, geothermal heat, wave, etc.).

Converting biomass to energy

Biomass is converted to energy through various processes, including:

- Direct combustion (burning) to produce heat
- Thermochemical conversion to produce solid, gaseous, and liquid fuels
- Chemical conversion to produce liquid fuels
- Biological conversion to produce liquid and gaseous fuels

The most popular technique for transforming biomass into usable energy is direct burning. For the purpose of heating buildings and water, providing process heat for industry, and producing power in steam turbines, any biomass can be burned directly.

Pyrolysis and gasification are two methods of converting biomass using high temperatures. Both processes involve heating biomass materials in sealed tanks called gasifiers. The main differences between them lie in the temperatures used and the presence of oxygen. Pyrolysis involves heating organic compounds to temperatures of 800-900°F (400-500°C) with little to no oxygen. This process produces various fuels such as charcoal, bio-oil, sustainable diesel, methane, and hydrogen from biomass. To create renewable diesel, gasoline, and jet fuel, bio-oil produced by fast pyrolysis is processed with hydrogen at high temperatures and pressures using a catalyst. Gasification, on the other hand, requires heating organic materials to temperatures between 1,400°F and 1,700°F (800°C and 900°C) with controlled amounts of oxygen and/or steam injected into the vessel. This process produces synthesis gas or syngas. Syngas can be used as a fuel for gas turbines, which generate electricity and provide heating, or in diesel engines. The hydrogen component of syngas can be separated and used in fuel cells or burned. The syngas can also be further processed using the Fischer-Tropsch process to create liquid fuels (Office of Energy Efficiency and Renewable Energy).

These thermochemical conversion processes offer ways to convert biomass into various useful fuels and energy sources, providing alternatives to traditional fossil fuels.Researchers are examining ways to enhance current techniques and create new strategies for converting and utilising more biomass for energy.

The transesterification process chemically converts vegetable oils, animal fats, and greases into fatty acid methyl esters (FAME), which are used to produce biodiesel. This process allows for the transformation of these materials into a renewable fuel source (U.S. Energy and Information Administration). Anaerobic digestion is another method that utilizes biomass to generate sustainable natural gas. Biomass is broken down in the absence of oxygen, producing biogas or biomethane. This process is employed in sewage treatment facilities, dairy farms, livestock operations, and landfills where renewable natural gas can be produced. The resulting biogas can be used similarly to natural gas derived from fossil fuels (U.S. Energy and Information Administration). Fermentation is a process that converts biomass into ethanol. This biofuel is commonly used in vehicles as an alternative to gasoline. Ongoing research aims to improve existing techniques and develop new strategies for efficiently converting and utilizing a greater amount of biomass for energy purposes.

4. Policies related to Bioenergy

- The best bioenergy policy initiatives are those that are clearly motivated and are a part of a long-term bioenergy plan. A vision should highlight important regional or national assets that could serve as the foundation for bioenergy solutions, such as industrial assets, infrastructure for trade, and feedstocks. Almost all effective bioenergy initiatives have expanded upon opportunities that were in a certain way previously present in the nation.

- It appears that long-term policy predictability and consistency are essential for the efficient development of bioenergy options. This suggests that regulations should take into account the distinctive qualities of the available options and the likelihood that they would require significant solutions. The term is defined, which increases policy predictability but does not indicate that all policies must be maintained eternally.

- Market access is necessary for almost all biofuel technology. Grid connectivity is the main issue with biomass-to-electricity conversion, and it needs to be addressed at the level of the power distribution network. For reliable market access for biofuels, standardization is essential, and national standards must converge into ones that are recognised internationally.

- A bioenergy policy approach should give agriculture, forestry, and waste priority because all bioenergy solutions depend on the availability of feedstock. Harmonizing feedstock demand from the food, feed, and wood processing industries, as well as the bioenergy industry, will depend on long-term support for productivity increases in these sectors. This is essential for minimising effects in markets for agricultural commodities.

Impact of greenhouse gas emissions from direct and indirect land use change on the greenhouse gas balances of biofuels?

In lifecycle studies of GHG emissions, the benefits of bioenergy are expressed in terms of GHG (Greenhouse Gas) emissions reductions when compared to conventional fossil routes. However, uncertainties in the climatic impact of bioenergy chains as well as conflicting study results are caused by the lack of high-quality empirical data for some elements and a widely accepted methodology (e.g., how by-products are accounted for). Some conclusions can be drawn confidently despite the uncertainties in the data and methodologies.

The main alternative for reducing climate change and maintaining energy security in the transportation sector may be biofuels. Fischer Tropsch diesel and transport fuels made from less prevalent oil sources have higher lifetime GHG emissions than the gasoline and diesel used today. The debate over whether to use biomass for stationary energy or transportation may eventually lose its significance. Modern bioenergy systems may increasingly include biorefinery technologies that provide power, heat, solid biofuels, chemicals, and other products in addition to liquid or gaseous biofuels for transportation. The primary driving forces are the synergies that can be accessed with increased total energy efficiency and resource efficiency gained by combining approaches, as well as the possible additional value from producing a variety of products.

5. Bioenergy - It’s Recent advancement and future prospective

Microalgal bioenergy production - The world's expanding energy demand and the results of global warming brought on by the combustion of fossil fuels have made it necessary to investigate and develop alternative clean, green, and sustainable energy resources. among other alternatives for sustainable energy. Three conversion technologies—biochemical, thermochemical, and chemical conversion—are used to transform microalgal biomass into biofuels. Over the past few decades, microalgae have gained recognition as a promising feedstock for the creation of bioenergy. Their lipid content has the ability to manufacture biodiesel, but their carbohydrate content can be used to make fermentative bioethanol and biobutanol. After lipid extraction and ethanol fermentation, microalgae can also be used to produce gaseous biofuels like biomethane and biohydrogen, or even only their byproducts (18). With up to 64% of starch per dry cell weight, microalgae species such as Chlamydomonas *sp., Chlorella sp., Spirulina sp., Spirogyra sp*., and *Dunaliella sp*. are suitable for use as potential feedstock (18,19). In addition, microalgae have high rates of biomass production, photosynthetic activity, and CO_2 biosequestration (20). Because they lack the lignin cross-linking structure of terrestrial plants, microalgae can grow and float in seawater and wastewater while also producing higher amounts of sugar substrates for fermentation. Additionally, per area of cultivation, microalgae produced 10 times more bioethanol than corn. Recent years have seen the incorporation of engineering methods into microalgae culture systems, resulting in the production of microalgae biomass with higher carbohydrate contents and, consequently, higher bioethanol yields. One example is *Chlamydomonas reinhardtii*, which showed 71% of its carbohydrate content when grown in a two-stage fed-batch photoautotrophic system. (21)

Industrial Waste - Waste from various industries, particularly the food business, could be used to make biofuels. The choice of inexpensive feedstock is actually crucial for the manufacturing of biofuels. Food waste is being produced at an ever-increasing rate. In scientific literature, the terms "food loss" and "food waste" relate to the identification of items meant for human consumption that may be polluted, deteriorated, discarded, or lost. Food loss and waste have an impact on the environment, causing landfill final disposal to emit greenhouse gases like methane. Additional negative effects of food loss and waste include resource depletion and disruption of biochemical processes (22). Since their removal and treatment are expensive, turning food processing wastes into biofuels is undoubtedly going to be a promising strategy. Furthermore, the cellulose, hemicelluloses, lignin, lipids, organic acids, proteins, and starch found in food processing wastes can be used as a source of carbon and nutrients for the creation of biofuels (23).

Biofuel Crops – Energy crops have a huge potential to supply the future energy needs of a population that is constantly expanding. The energy yield and subsequent biofuel conversion process depend greatly on the choice of the biofuel crop. C4 crops, such as Switchgrass (*Panicum virgatum*), *Miscanthus*, and *Sweet Sorghum*, are profitable to farm because they can flourish on barren ground and provide more biomass. Additionally, they have additional distinguishing qualities like a higher photosynthetic output and a higher rate of CO_2 collection compared to C3 crops. They are also resistant to aridity (24).

Miscanthus - A dozen or so grass species with an Eastern Asian origin make up the genus *Miscanthus*. As a possible biomass crop, it has garnered a lot of interest. It is a fast-growing perennial C4 grass that may produce 8 to 15 tonnes of dry weight per hectare with minimal food input. The most cold-tolerant C4 species have been discovered to be *Miscanthus* species, which can sustain strong CO2-assimilation at temperatures as low as 15 °C. *Miscanthus* may be completely exploited for the direct production of heat and electricity as well as for the indirect production of biofuels like methanol and ethanol (26).

Panicum virgatum (Switchgrass) - Switchgrass is a crucial crop for biofuels. It is an adaptable species of grass native to North America, and there are two main ecotypes: lowland and upland. Switchgrass is incredibly flexible and may thrive in a variety of environments, including those with inferior soil quality. Additionally, it has a reputation for having a high tolerance for cold, sickness, and insects. It is a very prolific crop when used as a biofuel resource; some studies have even reported yields of 15 mg ha1. Switchgrass might be burned directly to produce power, either on its own or in conjunction with coal. The biomass can also be transformed into liquid or gaseous forms that are high in energy. Both biological platforms and thermochemical technologies are used in the conversion of biomass. The first technique uses a fermentation and saccharification process to turn biomass into ethanol or other similar liquid fuels. The thermochemical technique uses gasification and pyrolysis. Due to its versatility, high productivity, and possible ease of integration into current agricultural operations, switchgrass as a feedstock for biofuels has attracted significant interest (26).

Sorghum bicolor (Sweet Sorghum) - It is a new generation bioenergy crop that utilises soil nutrients very effectively and has a very efficient photosynthetic system (C4). It has a lot of appealing qualities that make it a great renewable energy source. The stalk of sweet sorghum has liquid that is high in sugar. Its composition, which includes sucrose, cellulose, glucose, and hemicelluloses, makes it an excellent substrate for the manufacture of bioethanol. It has a variety of intriguing characteristics, including quick development, high sugar accumulation, the ability to produce biomass, tolerance of water lodging, resilience to salinity and drought, and quicker maturation under hot conditions and brief days (25). Producing bioethanol from sweet sorghum will undoubtedly help conserve the finite supplies of fossil fuels while also lowering greenhouse gas emissions. According to estimates, using sorghum to produce ethanol and green electricity will save roughly 3500 L of crude oil equivalents per hectare of cultivable land. Sorghum is a distinct species as a result. Because its genome sequence is publicly available, this crop has a better chance than ever of serving as a model crop for studies on the production of first and second-generation biofuels.

Furthermore, by combining agronomic techniques, genetics, and processing technologies, sorghum can be enhanced even further as a bioenergy crop (26).

Agricultural Waste - The human population is growing every day, which causes huge amounts of different kinds of waste to be produced. As waste output has grown, so has the issue of disposal. It is not economically possible to invest energy in the disposal of waste; but, using waste to produce energy would be promising. A 5% biomass energy production rate from agricultural waste has been approximated. Beets, corn, fruits, and sugarcane are included in agricultural biomass as are cobs of corn stover, leaves, rice husk, rice straw, and stalks, which are included as nonfood-based components. Ash, cellulose, hemicellulose, lignin, and protein make up the bulk of agricultural waste (27). A variety of techniques are used to pretreat lignocellulosic biomass, including physical, chemical, physicochemical, biological, and combination pretreatments. It is followed to use physical pretreatment techniques such as chipping, milling, grinding, freezing, and radiation. These techniques lead to a decrease in particle size while also increasing the surface area of lignocellulosic materials. Acids like H_2SO_4 and HCl are used in chemical pretreatment to better the enzymatic hydrolysis of lignocellulosic biomass to release fermentable sugars. Additionally, alkalis including ammonia, calcium hydroxide, potassium hydroxide, and sodium hydroxide are used to treat lignocellulosic biomass. Polysaccharides are solubilized by alkaline pretreatment, which also increases porosity. The process of treating chemicals with ozone, or ozonolysis, is another type of chemical pretreatment. In fact, using this technique causes lignocellulosic wastes to contain less lignin (26). Another chemical pretreatment technique that can remove both lignin and carbohydrates simultaneously is ionic liquid pretreatment. In response to treatment with organic solvents, lignocellulosic material is delignified. Ammonia fiber explosion pretreatment, CO_2 explosion pretreatment, liquid hot water pretreatment, steam explosion pretreatment, ultrasonication, and wet oxidation (WO) pretreatment are a few examples of physicochemical pretreatment techniques (27). Enzymatic pretreatment and treating with bacteria are examples of biological pretreatments. A few examples of combined pretreatment techniques are combined alkali and electron beam irradiation, combined alkali and ionic liquid, combined alkali and photocatalysis, combined biological and dilute acid, combined biological and steam explosion, combined dilute acid and microwave, combined enzyme hydrolysis and superfine grinding with steam, and combined enzyme hydrolysis and steam explosion (27). As a result, it becomes crucial to use alternative sources in order to produce H_2 in a sustainable, environmentally friendly, and renewable manner. Biological processes, which are more energy-efficient and environmentally benign than physicochemical ones, could be one method for producing H_2. These biological processes include photo-fermentation, dark fermentation, direct biophotolysis, and indirect biophotolysis (29). Due to its ability to break down organic wastes and high H_2 production rate, dark fermentation is known to be the most practically applicable biological process among those used to produce H_2. Mixed cultures of the bacteria *Clostridium sp., Enterobacter sp., Lactobacillus sp., Megasphaera sp., Prevotella sp.,* and *Selenomonas sp.* may perform dark fermentation (30). Additionally, lignocellulosic wastes including corn stover, bean husks, rice straw, wheat straw hydrolysate, and vegetable waste have all been used to produce biohydrogen. The most effective method for producing biohydrogen has been determined to be heating lignocellulosic biomass with H_2SO_4 or NaOH pretreatment.

6. Environmental impact of Bioenergy

Because it is renewable and abundant, bioenergy offers clear advantages over traditional fossil fuels and is therefore essential in preserving the nation's energy security. However, it is still unknown whether the rise of bioenergy may potentially result in serious environmental changes. We also have to acknowledge the fact that production of bioenergy can have a negative impact on the environment in terms of air and water pollution, greenhouse gas emissions, biodiversity and soil organic carbon, and soil erosion, but the negative effects can be varied greatly depending on the type of biomass, the location of the land, and the management techniques. Hence finding the optimum bioenergy crop kinds, suitable cultivation places, and best management techniques will help the environment and the long-term growth of bioenergy.

Although bioenergy accounts for only 14% of global energy consumption currently (World energy resources 2016) (31). In the foreseeable future, bioenergy holds a huge amount of promise. Sustainable bioenergy production can also effectively lower the danger of energy poverty and promote economic growth, particularly in developing nations. Scientists from all over the world have given the balance between bioenergy production and environmental protection a lot of thought, taking into account various strategies, including optimum management practices (BMPs). However, because of the complexity of the bioenergy production system and the paucity of information, it is still unclear what the total environmental effects of bioenergy production will be. Still bioenergy production via crops can provide multi fold benefits to the environment and humans.

Phytoremediation - By eliminating or degrading toxins, plants are used in phytoremediation to treat contaminated soil, sediments, and groundwater. This technique is cutting-edge, economical, and has broad application. The soil's quality could be improved by removing heavy metals through phytoremediation at bioenergy plants. The method also has the benefit of treating contaminated sites without digging. In order to clean up heavy metal-contaminated land, phytostabilization and phytoextraction are the main phytoremediation techniques used. Utilizing plants with roots that accumulate reduces the bioavailability of metals stable in the substrate. Utilizing plants with a high capacity for accumulating heavy metals from soils, sediments, and water is known as phytoextraction. In order to clean up metal-contaminated land, this strategy appears to be economically feasible (33).
However, choosing the right plant is essential for effective phytoremediation. The choice of plant is based on its availability, climate adaptation, capacity to remove heavy metals, rate of biomass production, and economic values. For example: to boost crop productivity, fields are fertilised with a lot of nitrate fertilisers. Nitrate pollution of the surface and groundwater is caused by the excessive use of nitrate fertilisers. There aren't many bioenergy plants that have the capacity to clean up water or soil toxins. *Poplar trees* are known to gather significant amounts of nitrate from streams that drain agricultural regions. Similarly *Miscanthus plants* are employed in phytoremediation as well. Due to its perennial nature, high productivity, superior growth rate, effective CO_2 sequestration, increased water consumption efficiency, and capacity to prevent soil erosion, the crop is recommended in phytoremediation (33).

Carbon Sequestration - Removing CO_2 from the atmosphere through the action of plants is known as carbon sequestration. Through a high biomass accumulation, bioenergy crops reduce atmospheric CO_2. By boosting carbon sequestration through high biomass output and deep root systems, perennial crops have the potential to improve soil quality. From this point forward, bioenergy crops could be employed to capture atmospheric CO_2 and increase biomass productivity for the production of bioenergy (33).

Soil Quality - Common farming practices and crop features have an impact on soil quality by altering the availability of organic matter, soil structure, and pH. For instance, although giant reed and cardoon significantly deplete nutrient resources, miscanthus, switchgrass, and other fiber crops have milder nutrient requirements. To preserve soil quality, appropriate nutrients must be added to the soil. Additionally, supplementing with nutrients requires careful attention to detail. Sweet sorghum and potato crops, for instance, require phosphorus concentrations that are relatively lower. Crops require applications of potassium and nitrogen in moderate amounts to prevent plant starvation. Insufficient nutrient uptake lowers plant biomass, and nutritional deficiencies manifest externally as symptoms. Sunflower, gigantic reed, and cardoon all exhibit more severe nitrogen shortages. High potassium shortages are also present in giant reed, cardoon, sugar beet, sweet sorghum, reed canary grass, and wheat (33).

Biodiversity - The biodiversity of nature is decreased by a number of environmental causes, with land conversion, deforestation, and grassland conversions contributing significantly. Growing bioenergy crops could be used to regulate the majority of these environmental concerns. Bioenergy crops help to combat climate change by lowering greenhouse gas emissions and preserving biodiversity. Additionally, the amount and variety of birds and insects increases during the blooming season of other crops, especially in sunflower fields. However, because annual crops have a short influence on the soil and have high growth requirements, their production lowers biodiversity. The development of lignocellulose-based biofuel systems that utilise a variety of feedstocks may increase the diversity of agricultural landscapes and the amount of ecosystem services provided by arthropods. For instance, perennial grasses with high lignocellulose content favour soil micro-fauna, minimise soil tillage and pesticide usage, yield high above and below ground biomass, and shelter both invertebrates and birds. Because they have longer life cycles and provide habitat for birds, animals, and other wildlife, willow and poplar plants support higher biodiversity than perennial grasses. The total impact of these crops on biodiversity, however, can be insignificant or even negative. Eucalyptus is a bioenergy plant, however because of the cultivation's more harsh management, it does not sustain biodiversity (33).

Water and Minerals - Bioenergy crop cultivation can be so water consuming as to jeopardise the availability of natural water resources. Therefore, when planting bioenergy crops, it is important to evaluate how much water the crop would need. Water scarcity may make it difficult for bioenergy crops to become productive sources of biofuel. For arid and semi-arid environments, careful selection of bioenergy crops with water stress tolerance is necessary. Some deeply rooted biofuel plants can withstand droughts and effectively trap carbon. However, these crops alter soil water and nutrient dynamics, which has a detrimental effect on biodiversity. The crops of corn, sugar cane, and oil palm are best suited to thrive in tropical regions with significant rainfall because they require more water for yield. Potato, hemp, and sugar beet also have a significant negative influence on water resources. However, eucalyptus and miscanthus plants often have less of an influence on water supplies. It is well recognised that bioenergy crops can alter soil nutrients. For instance, Pb, Ni, and Cu are accumulated in the roots and shoots of the sorghum plant. The depletion of soil mineral ore is somewhat reduced by the application of phosphate and potassium to bioenergy crop fields. Annual crops' nutrient use patterns are not considerably different from perennial crops', which require less macronutrients overall. Eucalyptus and willow plants have less of an impact on mineral resources than sweet sorghum and potatoes, which have higher risks of nutrient depletion (34).

Role of Machine Learning to boost bioenergy

Future generation of renewable and sustainable energy sources may greatly benefit from the development and implementation of bioenergy and biofuels conversion technology. However, it is challenging to create models based on experience or theory for precise forecasts due to the complexity of bioenergy systems and the limitations of human comprehension. Machine learning (ML) and recent advancements in data science may open up new possibilities. The most recent developments in ML-assisted bioenergy technologies, including as lignocellulosic biomass energy consumption, microalgae farming, and biofuels conversion and application, are examined in depth. Comprehensive analysis is done of the benefits and drawbacks of ML in bioenergy systems.

Here a few studies of ML Applications in Bioenergy production:

Feedstock

Mahanty et al. predicted specific methane yield in the production of biogas from industrial sludge using ANN (Artificial Neural Networking) and statistical regression models. In comparison to the statistical regression model, the ANN model performed better. It was discovered that chemical industrial sludges significantly affect the amount of methane in the biogas produced (35). The viscosity, Flash Point (FP), density, higher heating value, and oxidative stability of biodiesel made from sunflower oil, peanut oil, hydrogenated coconut oil, hydrogenated copra oil, beef tallow, rapeseed oil, and walnut oil were predicted by *Mairizal et al.* using multiple linear regressions. The findings suggested that using PU/MU as an independent parameter might improve prediction accuracy (36). Multiple NonLinear Regression (MNLR) and ANN were utilised by *Tchameni et al*. to forecast the rheological characteristics of used vegetable oil for the generation of biodiesel. Performance-wise, the ANN model outperformed the MNLR approach (37). *Dahunsi* estimated the methane yield in the structural elements of biomass using single and multiple linear regressions. The biomass's chemical make-up and methane potentials were shown to be largely correlated (38).

Biodiesel

The studies presented in the biodiesel production phase are further divided into categories, based on the results of the ML models: quality, yield, and process efficiency.

1. Quality Estimation

   The ideal conditions for producing the desired nanocrystalline size of the mesoporous SO_3HZnO catalyst were determined by *Soltani et al*. using the ANN model. The ideal conditions included a calcine temperature of 700 °C, a reaction temperature of 160 °C, a reaction period of 18 min, and a Zn concentration of 4 mmol (39). Least Squares Boosting (LSBoost) was combined with the polynomial chaos expansion approach by *Ahmad et al*. to produce vegetable oil-based biodiesel under ambiguous conditions. In response to 1% uncertainty in each model's input variable, the target output's projected values had an average Mean Absolute Deviation Percent (MADP) value of 0.84 (40).
2. Yield Estimation

   In several research based on biodiesel yield prediction using ML techniques, biodiesel was produced using jatropha algae, castor oil, and anaerobic sludge, for example. An ANN model was created by *Kumar et al.* to forecast biodiesel yield using different jatropha-algae oil blends as inputs (41-43). An ANN model was employed by *Banerjee et al.* to forecast the fractional generation of FAME. Additionally, they created a kinetic model combining the computational and experimental data. The rate constants of the kinetic model were estimated using experimental data as well as ANN-based forecasted data. Within an error of 8%, the ANN model accurately predicted the% FAME yield (41).
3. Estimation and Optimization of Process Conditions and Efficiency

   RSM (Response Surface Methodology) and ANN were used by *Karimi et al.* to estimate the FAME content and exergetic efficiency in the production of biodiesel from used cooking oil. By maximising the input variables, the method successfully attained high quality and energetic efficiency of the process. The design variables included reaction duration, immobilised lipase concentrations, water concentrations, and methanol concentrations. The FAME content and exergy efficiency were 86% and 80.1%, respectively, with a catalyst concentration of 35%, 12% water content, 6.7 molar ratio of methanol to WCO, and 20 h of reaction time. (44) *Aghbashlo et al.* predicted Functional Exergy Efficiency (FEE), Normalized Exergy Destruction (NED), Universal Exergy Efficiency (UEE), and Conversion Efficiency (CE) in the manufacture of biodiesel using ANFIS with GA and linear interdependent fuzzy multi-objective optimization. The ideal values for residence time, methanol-to-oil molar ratio, and transesterification temperature were discovered to be 60 C, 10 min, and 6.20, respectively (49).

Biogas

1. Quality Estimation
   In order to simulate and optimise the operating conditions of Upflow Anaerobic Sludge Blanket (UASB) reactors for the production of biogas, *Tufaner et al*. employed ANN. A laboratory-scale UASB reactor's biogas yield was observed to be accurately predicted by ANN (46). *Asadi et al.* predicted the biogas production rate from an anaerobic digester using ANN and ANFIS with subtractive clustering, Fuzzy C-Means Clustering (FCMC), and grid division. The ANFIS-FCMC model performed better than the other sets of models, according to the findings (47).

2. Yield Estimation
   Under mesophilic and thermophilic conditions, *Ghatak and Ghatak* employed ANN to forecast the yield of biogas from animal manure, sugarcane bagasse, bamboo dust, and sawdust. The ability of ANN modelling considerably decreased the amount of processing time needed for process control (48). *Nair et al.* evaluated the biogas yield from the organic fraction of municipal solid, which included vegetable waste, food waste, and yard trimming, in an anaerobic bioreactor using ANN. It was concluded that a pH range of 6.6 to 7.1 and Total Volatile Solids (TVS) between 77 to 84% can lead to an optimum CH_4 recovery (49).

3. Optimization of Quality and Yield
   In order to optimise operating parameters, *Qdais et al.* also combined the ANN model with the GA (Genetic Algorithm), which led to a 6.9% improvement in yield (50). According to *Dibaba et al.*, the Upflow Anaerobic Contactor (UAC) had the best performance with an 87% COD removal rate and a hydraulic retention duration of 16.67 days, which led to a 7.4% increase in biogas output (51). To calculate and maximise the yield of biogas from co-digested cattle dung and Karanja seed cake, *Barik and Murugan* employed ANN and GA. When utilising a mixture of Karanja cake and cow dung, the product quality was higher than when using samples of cattle dung with a ratio of 1 cake of Karanja to 3 cattle dung (52).

Conclusion

The 21st century presents significant challenges in environmental pollution and climate change, necessitating a shift in energy production, especially in sectors like aviation, heavy transport, and manufacturing. Bioenergy technology offers a sustainable and reliable means of energy production through biological processes, aligning with global decarbonization efforts. Key renewable energy sources like biogas, bioethanol, coal, hydrogen, and biodiesel, along with advancements in data science and machine learning, are paving the way for innovative applications in bioenergy technology. However, rigorous certification processes must be followed to demonstrate environmental superiority. The path forward lies in harnessing biomass and bioenergy to meet energy demands sustainably, reducing greenhouse gas emissions, stimulating economic growth, and offering innovative waste disposal solutions.

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