BIOENERGY- A SUSTAINABLE AND RELIABLE SOURCEFOR CLEAN ENERGY

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-decarbonizes 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

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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 serve as a foundation for generating clean energy from sustainable sources. Substantial efforts have been devoted to exploring novel microbial systems and their capacities, understanding the molecular processes that facilitate microbial bioenergy generation, and enhancing the efficiency of established microbial bioenergy systems through significant investments.

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

I. 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, urbanization, 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 us and all other kinds of life on Earth in grave danger. In the year 2021, four key indicators of climate change—namely, greenhouse gas concentrations, rising sea levels, increasing ocean heat content, and ocean acidification—have reached their most alarming levels. This serves as a clear and undeniable sign that human activities are causing significant and enduring alterations to the planet's environment, affecting land, oceans, and the atmosphere on a global scale. Consequently, the imperative to break free from our reliance on fossil fuel-based energy and transition to sustainable and renewable energy sources has become an absolute necessity in addressing 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 foremost challenges humanity will face in the coming decades is ensuring a reliable supply of sustainable energy, particularly as we strive to combat climate change. Biomass stands out as a significant contributor to meeting future energy needs sustainably. Currently, it holds the title as the world's most extensive source of renewable energy and offers substantial potential for expansion in the domains of heat, electricity, and transportation fuel production. 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. This review provides a comprehensive examination of the prospects and challenges associated with the increased utilization of bioenergy. It delves into the opportunities and obstacles pertaining to resources, technology, practices, markets, and policy. The primary aim is to provide valuable perspectives on the potential and essential actions required to establish a sustainable bioenergy industry.

II. 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 originate from waste materials generated by various industries, including agriculture, food processing, and wood production, or they can be purposely cultivated for their energy content, known as energy crops. Dry and easily combustible feedstocks, such as woody biomass, are combusted in boilers or furnaces, causing water to boil, generate steam, and drive turbines for electricity generation. In contrast, food waste and other moisture-rich feedstocks are placed in sealed tanks where they undergo decomposition, releasing methane gas, also known as biogas. This generated gas can be harnessed for energy production or, as an alternative, integrated into the national gas infrastructure for heating and cooking purposes. Biomass energy is derived from solar energy captured through photosynthesis or the metabolic processes of living organisms. This energy is subsequently stored within the chemical bonds of carbon and hydrogen chains. Due to its ability to retain energy until required, biomass is occasionally likened to nature's solar battery, offering a more dependable and adaptable energy source compared to solar or wind energy.

From the earliest human civilizations until the onset of the industrial revolution, biomass served as the predominant energy source for heating and cooking. Approximately 10% of the world's primary energy supply is comprised of biomass, with the majority originating from wood. This positions biomass as the most extensively employed renewable energy source. In recent times, there has been a notable surge in interest surrounding the generation of heat, electricity, and transportation fuels from biomass. 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).

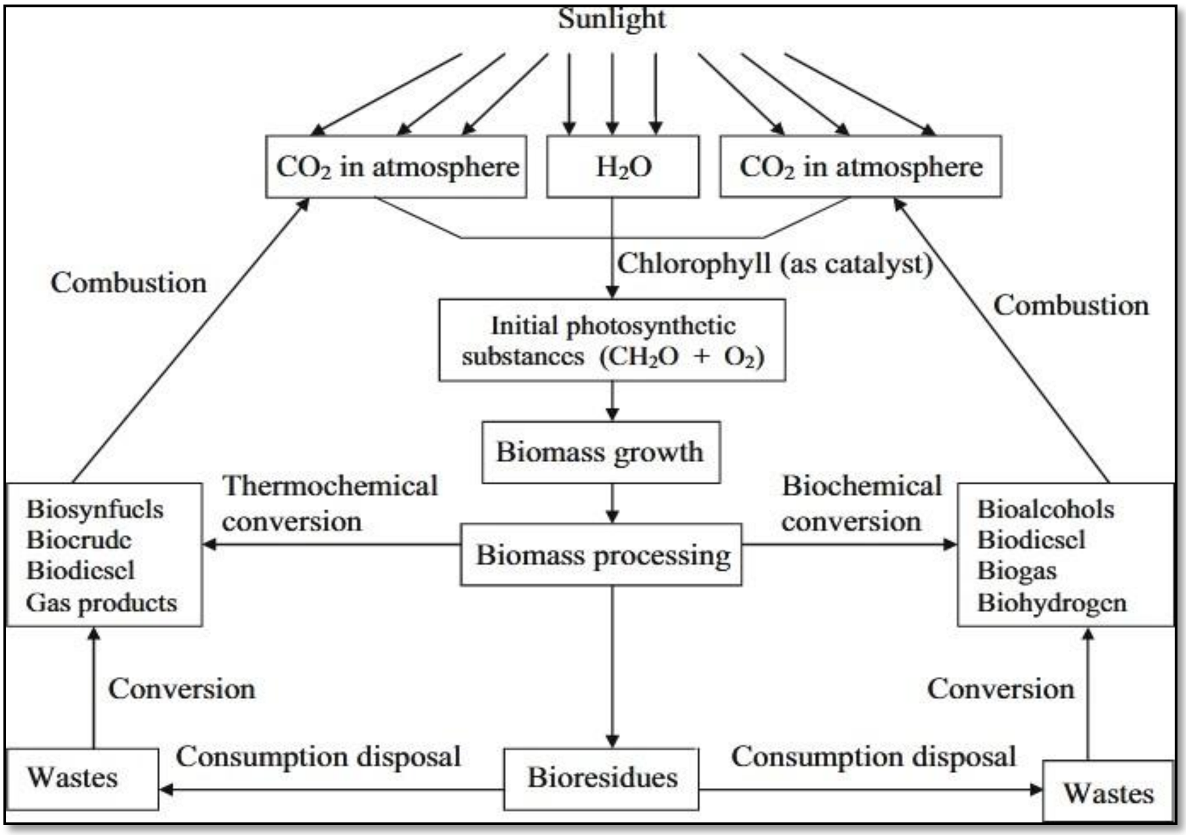

Figure 1: Carbon cycle, photosynthesis, and main steps of biomass technologies

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.

1. **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. Plant or algal biomass derives its initial energy from the sun, which allows for rapid renewal. Trees, crops, and municipal solid waste are all readily available and can be subject to careful management. 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 encompass the following:

- Wood and byproducts of wood processing, including firewood, wood pellets, wood chips, as well as sawdust and waste from lumber and furniture mills, along with black liquor derived from pulp and paper mills.
- Agricultural crops and related waste materials, such as corn, soybeans, sugar cane, switchgrass, woody plants, and algae, as well as residues from crop and food processing, primarily employed for biofuel production.
- Biogenic substances within municipal solid waste, encompassing paper products, cotton and wool items, as well as food, yard, and wood waste.
- Animal manure and human sewage utilized in the production of biogas or renewable natural gas.

The utilization of biomass for heating and cooking has a long history dating back to the earliest human settlements. Even today, wood remains the dominant biomass energy source in the market. Furthermore, there is a range of alternative sources, including food crops, various plant materials (both grassy and woody), agricultural and forestry residues, oil-rich algae, as well as the organic components of municipal and industrial waste streams. Innovatively, biomass energy can also be derived from landfill emissions, which primarily consist of methane, a key component of natural gas. This presents an eco-friendly alternative to the conventional fossil fuels typically employed for the production of energy, fuel, and various 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.

III. BIOENERGY TECHNOLOGIES

1. **Biofuels:** To meet transportation requirements, biomass undergoes conversion processes to produce liquid fuels, commonly referred to as biofuels, which include ethanol and biodiesel. 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. Utilizing solar energy, these bacteria combine carbon dioxide with water to create biomass at a superior rate and efficiency compared to terrestrial plants. Certain microalgae strains, abundant in oil content, can serve as the foundation for various transportation fuels, including biodiesel, "green" diesel, gasoline, and jet fuel. This approach helps mitigate the environmental impact of carbon dioxide emissions from sources like power plants.

2. **Biopower:** In biopower systems, renewable biomass fuels are transformed into heat and electricity through three primary methods: combustion, bacterial decomposition, or conversion into gaseous or liquid fuels. 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.

3. **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. The potential markets for bioproducts such as polymers, lubricants, solvents, adhesives, herbicides, and medications are extensive and diverse. However, caution is currently exercised when considering many first-generation bioproducts derived from biomass due to several reasons:

   - They may not deliver the promised environmental advantages unless the biomass feedstock is sourced responsibly.
   - They can contribute to indirect land-use change (ILUC), potentially accelerating deforestation.
   - They have the potential to negatively impact biodiversity.
   - Apart from sugar cane ethanol, they often provide limited and costly greenhouse gas reduction benefits.
   - They represent an expensive solution for enhancing energy security.

- They can contribute to increased food prices (16).

IV. BENEFITS OF BIOMASS

Biomass can provide an array of benefits.

1. **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).

2. **Reduced Greenhouse Gas Emissions:** Biomass-based bioenergy technologies release fewer greenhouse gases, particularly carbon dioxide (CO2), 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).

3. **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).

4. **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 feedstock’s, reducing net carbon emissions (56).

5. **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).

6. **Greenhouse Gas Emissions Reduction:** Biomass energy plays a significant role in reducing greenhouse gas emissions. When biomass is burned, it emits a comparable amount of carbon dioxide as fossil fuels. However, fossil fuels release "new" carbon dioxide into the atmosphere, which was originally sequestered through photosynthesis millions of years ago. In contrast, the carbon dioxide emissions from biomass are largely balanced by the carbon dioxide it absorbs during its growth cycle, although this depends on the energy input involved in its cultivation, harvesting, and processing. Research indicates that harvesting trees for biomass can result in a carbon penalty that takes several decades to recover from. Therefore, it is more preferable for biomass to be cultivated on previously cleared land, such as unused farmland, to mitigate this impact (6).

7. Foreign Oil Dependence Reduction: Biofuels serve as the sole renewable option for liquid transportation fuels, offering a means to reduce dependence on foreign oil. Biomass energy lends support to the agricultural and forest product industries. Primary biomass sources for energy production include municipal waste, residuals from lumber mills, and remnants from paper mills. Currently, the predominant feedstocks for biomass fuels are soybeans and maize grain, which are used in ethanol and biodiesel production, respectively. Additionally, emerging technologies developed by the National Renewable Energy Laboratory (NREL) are enabling the utilization of agricultural residues like wheat straw and maize stover (comprising stalks, leaves, and husks) in the near future. Looking ahead, dedicated energy crops such as algae, fast-growing trees, and grasses are poised to play a substantial role. These crops can be cultivated sustainably in areas where intensive food crops are impractical, offering a long-term solution (6).

V. WHAT IS THE QUANTITY OF BIOMASS UTILIZED FOR ENERGY PURPOSES?

In 2021, the United States derived approximately 4.8 quadrillion Btu (equivalent to 4,835 trillion British thermal units or TBtu) from biomass, constituting approximately 5% of the nation's overall primary energy consumption. Of this total, around 2,316 TBtu originated from biofuels, primarily ethanol, while 2,087 TBtu came from wood and biomass derived from wood. Additionally, 431 TBtu were sourced from biomass found in municipal solid waste, sewage, animal manure, and agricultural remnants.

Breaking down the use of biomass energy in 2021 by sector, the amounts in TBtu and their respective percentage shares were as follows:

(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%

As per data from the U.S. Energy and Information Administration, the industrial and transportation sectors hold a dominant position in both energy content and the overall annual U.S. biomass consumption percentage. Within the paper and wood products industries, biomass finds its use in combined heat and power plants, serving the dual purpose of generating energy for internal needs and supplying process heat.

In the transportation sector, the primary application of biomass is in the form of liquid biofuels, as highlighted by the U.S. Energy and Information Administration. Furthermore, firewood and wood pellets serve as heating sources in both residential and commercial settings. Additionally, the business sector is involved in the utilization and occasional sale of renewable natural gas produced through municipal sewage treatment facilities and landfills for waste disposal, as reported by the 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).

VI. HOW TO CONVERT BIOMASS INTO BIOENERGY?

Biomass stands out as a distinctive renewable resource in several respects. Unlike intermittent sources like wind and solar, which provide electricity that must be used immediately and connected to the grid, biomass is relatively easy to store and transport. In the production of bioenergy, biomass costs often constitute a significant portion, typically ranging from 50% to 90%. This is due to the absence of waste and residues, setting the economic dynamics of bioenergy apart from other renewable energy alternatives that primarily rely on free resources, such as wind, sunlight, geothermal heat, and wave energy.

Converting biomass to energy

Energy can be generated from biomass through diverse methods, which include:

- Direct combustion, leading to the production of heat.
- Thermochemical conversion, resulting in solid, gaseous, and liquid fuels.
- Chemical conversion, yielding liquid fuels.
- Biological conversion, giving rise to liquid and gaseous fuels.

Among these methods, direct burning is the most widely adopted approach for converting biomass into usable energy. 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 involves the chemical transformation of vegetable oils, animal fats, and greases into a substance called fatty acid methyl esters (FAME), which serves as a key ingredient in the production of 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.

VII. POLICIES RELATED TO BIOENERGY

1. 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.

2. 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.

3. Establishing market access is a crucial requirement for nearly all biofuel technologies. In the context of converting biomass into electricity, the primary challenge lies in achieving grid connectivity, which necessitates attention at the level of the power distribution network. To ensure dependable market access for biofuels, standardization plays a pivotal role, necessitating the alignment of national standards with internationally recognized ones.

4. When adopting a policy approach towards bioenergy, it is imperative to prioritize agriculture, forestry, and waste management, as these sectors are fundamental to the availability of feedstock for all bioenergy solutions. Achieving harmony in feedstock demand among industries like food production, animal feed, wood processing, and the bioenergy sector hinges on sustained support for enhancing productivity within these sectors. Such support is essential to minimize market disruptions for agricultural commodities.

VIII. HOW DO GREENHOUSE GAS EMISSIONS RESULTING FROM BOTH DIRECT AND INDIRECT LAND USE CHANGES AFFECT THE OVERALL GREENHOUSE GAS EQUILIBRIUM ASSOCIATED WITH BIOFUELS?

In assessments of GHG emissions throughout the lifecycle, bioenergy's advantages are quantified in the form of reductions in greenhouse gas emissions when compared to traditional fossil-based methods. Nonetheless, the uncertainties in gauging the climatic influence of bioenergy systems, along with contradictory findings in research, stem from the absence of robust empirical data for certain aspects and a universally accepted methodology, such as the standardized accounting of by-products. Despite these uncertainties in data and methodologies, certain conclusions can be confidently made.

The predominant alternative to combat climate change and ensure energy security in the transportation sector appears to be biofuels. However, it's worth noting that Fischer-Tropsch diesel and transport fuels derived from less common oil sources tend to exhibit higher lifetime greenhouse gas emissions compared to the gasoline and diesel currently in use. The ongoing debate over whether to allocate biomass for stationary energy or transportation purposes may become less significant with time. Emerging bioenergy systems are increasingly incorporating biorefinery technologies, which not only yield liquid or gaseous biofuels for transportation but also generate power, heat, solid biofuels, chemicals, and various other products. The driving forces behind this trend are the synergies achievable through enhanced overall energy efficiency and resource utilization when different approaches are combined. Additionally, there is potential added value in producing a diverse range of products from these systems.

IX. BIOENERGY - IT’S RECENT ADVANCEMENT AND FUTURE PROSPECTIVE

1. **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 can be harnessed for biodiesel production, while their carbohydrate content is suitable for the production of fermentative bioethanol and biobutanol. Following lipid extraction and ethanol fermentation, microalgae can also be employed in the production of gaseous biofuels, such as biomethane and biohydrogen, or even exclusively their byproducts (18). Microalgae species like *Chlamydomonas sp.*, *Chlorella sp.*, *Spirulina sp.*, *Spirogyra sp.*, and *Dunaliella sp.* boast starch levels of up to 64% of their dry cell weight, making them promising candidates as potential feedstock (18, 19). Moreover, microalgae exhibit rapid biomass growth rates, efficient photosynthetic activity, and effective CO2 capture (20). Unlike terrestrial plants, microalgae do not possess lignin's rigid cross-linking structure, allowing them to thrive and float in seawater and wastewater environments. This unique trait enables them to produce larger quantities of sugar substrates suitable for fermentation. Notably, microalgae can yield 10 times more bioethanol per unit of cultivation area compared to corn.

In recent years, engineering techniques have been integrated into microalgae cultivation systems, resulting in the production of microalgae biomass with elevated carbohydrate content, and consequently, higher bioethanol yields. For instance, *Chlamydomonas reinhardtii* achieved remarkable 71% carbohydrate content when cultivated using a two-stage fed-batch photoautotrophic system (21).

2. **Industrial Waste:** The potential to convert waste generated by various industries, especially the food sector, into biofuels presents an attractive opportunity. The selection of cost-effective raw materials is a critical factor in biofuel production. Notably, there is a growing abundance of food waste being generated. In scientific literature, the terms "food loss" and "food waste" refer to items originally intended for human consumption that may become contaminated, spoiled, discarded, or lost. The environmental consequences of food loss and waste are significant, as they contribute to greenhouse gas emissions, including methane, when deposited in landfills. Additionally, food loss and waste have adverse effects such as resource depletion and disruption of biochemical processes (22). Given the high costs associated with their disposal and treatment, converting food processing residues into biofuels holds great promise. Moreover, the cellulose, hemicelluloses, lignin, lipids, organic acids, proteins, and starch found in food processing waste can serve as valuable sources of carbon and nutrients for biofuel production (23).

3. **Biofuel Crops:** Energy crops possess significant potential to meet the ever-growing energy demands of an expanding population in the future. The energy output and subsequent biofuel production process are heavily influenced by the selection of the energy 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. This rapid-growing perennial C4 grass has the capacity to yield between 8 to 15 tonnes of dry weight per hectare while requiring minimal food input. Among the cold-tolerant C4 species, *Miscanthus species* have emerged as the most resilient, maintaining efficient CO2-assimilation even at temperatures as low as 15°C. *Miscanthus* can be fully utilized for direct heat and electricity generation and also indirectly serves as a source for biofuels such as methanol and ethanol (26).

   - ***Panicum virgatum*** **(Switchgrass) :** Switchgrass plays a vital role in the production of biofuels. This versatile grass species is indigenous to North America and can be categorized into two primary 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. The considerable interest in using switchgrass as a biofuel feedstock stems from its adaptability, impressive productivity, and the potential for seamless integration into existing agricultural practices (26).

- ***Sorghum Bicolor* (Sweet Sorghum):** This next-generation bioenergy crop effectively utilizes soil nutrients and boasts an exceptionally efficient C4 photosynthetic system. 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. Estimates suggest that the utilization of sorghum for ethanol production and green electricity generation could result in savings of approximately 3500 liters of crude oil equivalents per hectare of cultivable land. Sorghum stands out as a unique species in this regard. With its publicly accessible genome sequence, this crop is now better positioned than ever to serve as a model for research into the production of both 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).

4. **Agricultural Waste:** The ever-expanding human population leads to the generation of substantial quantities of diverse waste materials. With the increasing waste production, the challenge of disposal has grown in significance. Economically, expanding energy on waste disposal is not a feasible option. However, there is promise in utilizing waste for energy production. An estimated 5% biomass energy production rate can be derived from agricultural waste, encompassing materials like beets, corn, fruits, sugarcane, as well as non-food components such as corn stover, leaves, rice husk, rice straw, and stalks. 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. In the process, physical pretreatment methods such as chipping, milling, grinding, freezing, and radiation are employed. These methods result in a reduction in the particle size of lignocellulosic materials, simultaneously increasing their surface area. In chemical pretreatment, acids like H2SO4 and HCl are utilized to enhance the enzymatic hydrolysis of lignocellulosic biomass, facilitating the release of fermentable sugars. Additionally, alkalis such as ammonia, calcium hydroxide, potassium hydroxide, and sodium hydroxide are applied for the treatment of 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. Several physicochemical pretreatment techniques exist, including

ammonia fiber explosion, CO2 explosion, liquid hot water, steam explosion, ultrasonication, and wet oxidation (27). On the other hand, biological pretreatments involve enzymatic processes and treatment with bacteria. Combining different pretreatment methods is also common, such as combining alkali with electron beam irradiation, alkali with ionic liquid, alkali with photocatalysis, biological with dilute acid, biological with steam explosion, dilute acid with microwave, enzyme hydrolysis with superfine grinding and steam, and enzyme hydrolysis with steam explosion (27). To ensure sustainable, environmentally friendly, and renewable hydrogen (H2) production, alternative sources become imperative. Biological processes, which are more energy-efficient and environmentally benign compared to physicochemical methods, offer a promising avenue for H2 production. These biological processes encompass photo-fermentation, dark fermentation, direct biophotolysis, and indirect biophotolysis (29). Dark fermentation, known for its ability to break down organic wastes and high H2 production rate, stands out as the most practically applicable biological process (30). Mixed cultures of bacteria, including *Clostridium sp., Enterobacter sp., Lactobacillus sp., Megasphaera sp., Prevotella sp.*, and *Selenomonas sp.*, can effectively perform dark fermentation. Moreover, various lignocellulosic wastes like corn stover, bean husks, rice straw, wheat straw hydrolysate, and vegetable waste have been employed for biohydrogen production. Among these methods, heating lignocellulosic biomass with H2SO4 or NaOH pretreatment has proven to be the most efficient for biohydrogen production.

X. 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.

While bioenergy currently constitutes only 14% of global energy consumption (World Energy Resources 2016), its potential in the near future is immensely promising (31). Sustainable bioenergy production has the capacity to significantly mitigate the risks of energy poverty and stimulate economic growth, particularly in developing nations. Scientists worldwide have dedicated extensive efforts to striking a balance between bioenergy production and environmental preservation, considering diverse strategies such as Best Management Practices (BMPs). Nevertheless, due to the intricacies of the bioenergy production system and the limited available information, the comprehensive environmental impacts of bioenergy production remain unclear. Nevertheless, bioenergy production from crops has the potential to deliver manifold benefits to both the environment and humanity.

1. **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. Phytostabilization and phytoextraction stand as the primary phytoremediation methods employed for remediating heavy metal-contaminated soil. The use of plants with root systems that reduce the bioavailability of metals in the substrate is termed phytostabilization. Meanwhile, phytoextraction involves the use of plants with a strong ability to accumulate heavy metals from soils, sediments, and water. This approach appears to be economically viable for the remediation of metal-contaminated land (33).

Selecting the appropriate plant is crucial to ensure the effectiveness of phytoremediation. The selection of a plant depends on factors such as its availability, adaptability to the climate, ability to extract heavy metals, biomass production rate, and economic value. 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. This crop is recommended for phytoremediation due to its perennial characteristics, impressive productivity, rapid growth rate, efficient CO2 sequestration, enhanced water consumption efficiency, and its ability to combat soil erosion (33).

2. **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. Perennial crops have the capacity to enhance soil quality by increasing carbon sequestration through their substantial biomass production and extensive root systems. Consequently, these bioenergy crops can be harnessed to capture atmospheric CO2 and elevate biomass productivity for bioenergy generation in the future (33).

3. **Soil Quality:** Soil quality can be influenced by conventional farming methods and crop characteristics, which can modify the availability of organic matter, soil structure, and pH. For example, while giant reed and cardoon exert a significant drain on nutrient reserves, *miscanthus*, switchgrass, and other fiber crops exhibit less demanding 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. Potassium deficiencies are prevalent in giant reed, cardoon, sugar beet, sweet sorghum, reed canary grass, and wheat as well (33).

4. **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 establishment of biofuel systems centered on lignocellulosic sources, utilizing a range of feedstock options, holds the potential to enhance agricultural landscapes' diversity and amplify the ecosystem services offered by arthropods. For example, perennial grasses boasting substantial lignocellulose content are conducive to soil micro-fauna, minimize the need for soil tillage and pesticides, yield significant above and below-ground biomass, and provide refuge for both invertebrates and birds. Willow and poplar plants, due to their longer life cycles and capacity to offer habitats for birds, animals, and other wildlife, foster greater biodiversity compared to 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).

5. **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. The challenge of water scarcity poses a potential obstacle to the productivity of bioenergy crops in serving as viable sources of biofuel. In arid and semi-arid environments, the careful selection of bioenergy crops possessing water stress tolerance becomes imperative. Some biofuel plants with deep roots exhibit resilience to drought conditions and effectively sequester carbon. Nevertheless, the cultivation of these crops can disrupt soil water and nutrient dynamics, resulting in adverse effects on biodiversity. Corn, sugar cane, and oil palm are better suited for thriving in tropical regions characterized by abundant rainfall, as they demand higher water inputs for optimal yield. Conversely, potato, hemp, and sugar beet also exert a notable detrimental impact 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. As an example, sorghum plants accumulate Pb, Ni, and Cu in both their roots and shoots. The practice of applying phosphate and potassium to bioenergy crop fields helps mitigate the depletion of mineral ores in the soil to some extent. 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 resourcesthan sweet sorghum and potatoes, which have higher risks of nutrient depletion (34).

XI. ROLE OF MACHINE LEARNING TO BOOST BIOENERGY

The advancement and adoption of bioenergy and biofuels conversion technology hold substantial promise for future generations seeking renewable and sustainable energy sources. Nevertheless, the intricate nature of bioenergy systems and the constraints of human understanding make it challenging to create precise predictive models based on experience or theory. There is hope that recent strides in machine learning (ML) and data science could offer fresh avenues for exploration. This comprehensive review delves into the latest developments in ML-assisted bioenergy technologies, encompassing areas such as the utilization of lignocellulosic biomass for energy, microalgae cultivation, and biofuels conversion and utilization. Comprehensive analysis is done of the benefits and drawbacks of ML in bioenergy systems.

Here a few studies of ML Applications in Bioenergy production

1. **Feedstock:** *Mahanty et al.* employed both Artificial Neural Networking (ANN) and statistical regression models to forecast the specific methane yield in the biogas production process from industrial sludge. In direct comparison, the ANN model demonstrated superior performance. Their findings highlighted the significant influence of chemical industrial sludges on methane levels within the produced biogas (35). *Mairizal et al.* utilized multiple linear regressions to make predictions regarding the viscosity, Flash Point (FP), density, higher heating value, and oxidative stability of biodiesel derived from various sources such as sunflower oil, peanut oil, hydrogenated coconut oil, hydrogenated copra oil, beef tallow, rapeseed oil, and walnut oil. The findings suggested that using PU/MU as an independent parameter might improve prediction accuracy (36). *Tchameni et al.* applied both Multiple NonLinear Regression (MNLR) and Artificial Neural Network (ANN) techniques to predict the rheological properties of used vegetable oil used in biodiesel production. In terms of performance, the ANN model surpassed the MNLR method (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).

2. **Biodiesel:** The research regarding biodiesel production is categorized into three groups based on the outcomes of the Machine Learning (ML) models: quality assessment, yield optimization, and process efficiency enhancement.

   - **Quality Assessment:** *Soltani et al.* employed an Artificial Neural Network (ANN) model to determine the optimal conditions for producing nanocrystalline-sized mesoporous SO3HZnO catalyst. The identified optimal conditions encompassed a calcination temperature of 700°C, a reaction temperature of 160°C, a reaction duration of 18 minutes, and a Zn concentration of 4 mmol (39). *Ahmad et al.* combined Least Squares Boosting (LSBoost) with the polynomial chaos expansion method to manufacture biodiesel from vegetable oil under uncertain conditions. In response to a 1% uncertainty in each input variable of the model, the projected values of the target output exhibited an average Mean Absolute Deviation Percent (MADP) of 0.84 (40).

   - **Yield Estimation:** Numerous studies have delved into predicting biodiesel yield through the application of Machine Learning (ML) techniques. These investigations encompassed the production of biodiesel from various sources such as jatropha algae, castor oil, and anaerobic sludge. For instance, *Kumar et al.* developed an Artificial Neural Network (ANN) model to forecast biodiesel yield by utilizing different jatropha-algae oil blends as input parameters (41-43). In a similar vein, *Banerjee et al.* employed an ANN model to predict the fractional production of Fatty Acid Methyl Esters (FAME). They also devised a kinetic model that amalgamated computational and experimental data. The rate constants within this kinetic model were determined using both experimental data and predictions generated by the ANN. Remarkably; the ANN model accurately predicted the % FAME yield within an 8% margin of error (41).

- **Estimation and Optimization of Process Conditions and Efficiency:** *Karimi et al.* utilized Response Surface Methodology (RSM) in conjunction with Artificial Neural Networks (ANN) to estimate the Fatty Acid Methyl Ester (FAME) content and exergetic efficiency during the production of biodiesel from used cooking oil. This approach successfully achieved high-quality results and enhanced process energetics by optimizing key input variables. These variables encompassed reaction duration, immobilized lipase concentrations, water concentrations, and methanol concentrations. The resulting FAME content reached 86%, while the exergy efficiency attained 80.1%. These outcomes were realized with specific conditions, including a 35% catalyst concentration, 12% water content, a 6.7 molar ratio of methanol to waste cooking oil, and a 20-hour reaction time (44). *Aghbashlo et al.* predicted various efficiency metrics, including Functional Exergy Efficiency (FEE), Normalized Exergy Destruction (NED), Universal Exergy Efficiency (UEE), and Conversion Efficiency (CE), in the biodiesel production process. They employed Adaptive Neuro-Fuzzy Inference System (ANFIS) coupled with Genetic Algorithms (GA) and linear interdependent fuzzy multi-objective optimization. The optimal values for residence time, methanol-to-oil molar ratio, and transesterification temperature were determined to be 60°C, 10 minutes, and 6.20, respectively (49).

3. Biogas

- **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).

- **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).

- **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).

XII. 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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