

Review Article

Bioresource Processing: Challenges and Opportunities to Mitigate Climate Change and Enhance Sustainable and Renewable Energy - A Review

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Abstract - The escalating environmental crisis driven by fossil fuel dependency has intensified the search for sustainable energy alternatives. This review critically evaluates the potential of Fruit and Vegetable Waste (FVW), a largely untapped bioresource, to produce bioenergy, including biogas, bioethanol, biodiesel, and biohydrogen. The study consolidates fragmented literature by offering an integrated overview of production technologies, techno-economic constraints, environmental implications, and policy frameworks. Anaerobic digestion, enzymatic saccharification, transesterification, and dark fermentation processes are scrutinized for their viability, efficiency, and scalability. Emphasis is placed on pre-treatment innovations, process bottlenecks, and the necessity for standardization. Furthermore, the contribution of biofuels to greenhouse gas mitigation and air quality enhancement, contextualized within the Sustainable Development Scenario framework, is also explored. Through comparative case studies from both developed and emerging nations, it examines the trajectories of biomass integration, technological progress, and the effectiveness of supporting policy mechanisms. The review concludes by proposing a roadmap for overcoming operational, economic, and regulatory barriers to upscale FVW-based bioenergy production. In doing so, it highlights the transformative role of circular bioeconomy practices in achieving carbon neutrality and energy equity. This synthesis offers a timely reference for researchers, policymakers, and industry stakeholders committed to climate-resilient energy transitions.

Keywords - Fruit and Vegetable Waste, Bioenergy conversion technologies, Sustainable Development Goals, Climate Change Mitigation, Circular bioeconomy.

1. Introduction

1.1. Production Processes, Techno-Economic and Policy Challenges of Bioenergy Production from Fruit and Vegetable Wastes

The introduction Growing energy needs have become an important element in maintaining global competitiveness, but must be considered alongside the growing environmental problems associated with fossil fuel over-reliance. Such issues have led to energy concerns globally to find cleaner, more sustainable, and cost-effective forms of energy.

The rapid population growth, industrial development, and the resultant need for energy consumption stress the necessity for such a transition. In seeking viable substitutes for traditional fossil fuels, it necessarily follows that these alternative fuel sources must be assessed for cost, feasibility, and ability to provide for a voracious energy need, along with their environmental benefit and availability [1].

Biomass energy development has the potential to provide a beneficial two-fold solution to our current major energy and environmental crisis. It is attractive in terms of its sustainability, economics, and ecology [2]. In this sense, biofuels such as bioethanol, biodiesel, biogas, and biohydrogen can be of great help in increasing energy efficiency, environmental protection, and energy security. Bioenergy, in this context, is seen as a key and transformative technology that can provide a path forward to reduce fossil fuel use and greenhouse gas emissions [2, 3].

1.2. Review of Biofuel Production: A Sustainable Method from the Points of View of Sustainable Development, The Environment, and Climate Change

The International Energy Agency (IEA) projects that global reliance on fossil fuels will surge by approximately 33% by 2035 [3, 4]. Alarmingly, this trend is anticipated to contribute an additional 87 gigatons of CO₂-equivalent



emissions by 2050, intensifying the pace of climate change and its cascading environmental repercussions [5, 6]. Compounding the issue, the combustion of traditional biomass sources like wood releases an estimated 1.4 million tons of methane annually. More broadly, biomass burning is responsible for nearly 40% of global CO₂ emissions and contributes roughly 38% of hazardous tropospheric pollutants. These sobering statistics have galvanized the scientific community to accelerate the search for sustainable, environmentally benign, bio-based fuel alternatives that can mitigate these harmful outcomes [7, 8].

A range of cutting-edge and emerging technologies has been developed globally to enable the sustainable production of renewable biofuels from biomass, offering a viable pathway to meet the escalating energy needs while addressing the environmental challenges outlined earlier [9]. Biomass-derived biofuels encompass a diverse array of energy carriers, including densified solid forms such as pellets, briquettes, cubes, and char; upgraded liquid fuels like biodiesel, bioethanol, and bio-oil; and gaseous alternatives such as methane, syngas, and hydrogen produced via Fischer–Tropsch synthesis [10].

Biomass is abundant in biodegradable organic material and is used to generate biofuels [11]. They undergo thermochemical transformations into heat, syngas, bio-oil, and charcoal via gasification, pyrolysis, liquefaction, combustion, and torrefaction [7]. Similarly, various biochemical processes produce biofuels, especially bioethanol, biodiesel, biogas, and biohydrogen [12]. The advantages of biofuels compared to fossil fuels include: (i) their oxygenated characteristics that enhance usability and renewability [13], (ii) their sustainability, as they are derived from biomass, devoid of sulfur, and biodegradable, (iii) their combustion aligns with the CO₂ cycle that make them predominantly carbon-neutral, and (iv) their status as environmentally friendly energy sources. Future advancements in biofuel technology will facilitate the development of a sustainable energy source and enhance energy security [14].

Much of the work by researchers has focused on investigating the potential of various Fruit and Vegetable Waste (FVW) as feedstocks for bioenergy production. Most reviews independently reported on production processes and challenges, bioethanol production, biodiesel production, biohydrogen production, environmental and climate change perspectives, and the production processes and challenges.

This has resulted in a fragmented body of knowledge, marked by conceptual ambiguity, unclear direction, and a piecemeal approach that hinders a comprehensive understanding of the bioenergy production landscape. A disjointed perspective of this type can result in poorly informed and less-than-optimal decision-making. To fill this void, the present review seeks to provide a consolidated

perspective of the existing progression, technological pathways, and policy challenges of producing bioenergy from FVW worldwide.

Most importantly, this review identifies technological innovation as a critical determinant towards increasing the efficiency of FVW-to-bioenergy conversion processes. It further details potential strategies to work around ever-present technical bottlenecks, the most important cost drivers, as well as areas of improvement for capital and operational expenditures. It further proposes actionable mechanisms to support FVW as a feedstock that is technically, economically, and environmentally preferable for widespread use in the renewable energy transition.

The present study seeks to explore the adoption patterns of biomass energy across a range of representative countries, examining how technological progress and policy instruments have shaped its deployment. Through this, the study provides critical insights into the evolving role of biomass in the broader context of energy transitions. As the global momentum toward carbon neutrality intensifies, the deliberate and strategic incorporation of biomass into national energy portfolios emerges as an essential pillar of a resilient, low-carbon, and diversified energy future.

Despite significant global progress in exploring FVW for bioenergy production, the current body of knowledge remains fragmented. Most existing reviews tend to focus narrowly on individual fuel pathways, such as bioethanol, biodiesel, or biogas, without offering a consolidated perspective on their comparative efficiencies, techno-economic trade-offs, and policy relevance. This piecemeal approach has created conceptual ambiguity and hindered the development of a unified roadmap for scaling FVW-to-bioenergy technologies. Moreover, there is still no comprehensive synthesis linking technological innovations (e.g., pre-treatment methods, enzymatic hydrolysis, and advanced catalysts) with cost-effectiveness, environmental performance, and regulatory mechanisms. As a result, decision-makers often face uncertainties regarding the viability and sustainability of FVW-based bioenergy adoption.

The novelty of the present work lies in its integrative perspective. This review not only consolidates the state of knowledge across all four major FVW-derived biofuels, such as biogas, bioethanol, biodiesel, and biohydrogen, but also systematically analyzes their process bottlenecks, pre-treatment innovations, techno-economic drivers, and regulatory challenges within the context of Climate Change Mitigation. Furthermore, unlike earlier works, this study explicitly connects FVW bioenergy pathways to the Sustainable Development Scenario (SDS) and circular bioeconomy frameworks, thereby highlighting their role in achieving carbon neutrality and energy equity. By situating FVW bioenergy at the intersection of technology, economics,

and policy, this review provides a unique consolidated roadmap that enables researchers, industry, and policymakers to understand not only the scientific feasibility but also the operational and governance mechanisms required to upscale FVW-based bioenergy solutions globally.

To address this gap, the present review integrates technological, economic, environmental, and policy perspectives into a single framework. By consolidating insights across biogas, bioethanol, biodiesel, and biohydrogen pathways, this study aims to clarify process bottlenecks, highlight cost and scalability drivers, and propose actionable strategies for overcoming existing barriers. In doing so, the review positions FVW as a critical but underutilized feedstock within the circular bioeconomy, while identifying the innovations and policies required to transform it into a mainstream renewable energy source.

2. Global Biofuel Sustainable Development Scenario

The IEA has established the SDS, which provides an excellent framework for understanding people and world safety [10, 15]. By rebuilding the energy market and tackling the air pollution problem, nations collaborate to reduce the effects of climate change significantly [16]. To meet SDS, transport biofuel use requires that biofuel production be tripled by 2030 (to around 280 Mtoe), or 10% of the world's transportation fuel demand, as compared to the present 3%. Consequently, the SDS climbed 6% in 2019 to 96 Mtoe (161 billion liters) [3]. Despite early momentum, the average biofuel production growth over the following five years stagnated at just 3%, falling significantly short of the sustained 10% annual increase needed to meet 2030 targets. Bridging this gap will require not only consistent and strategic policy direction but also technological innovation aimed at lowering production costs and adapting market structures and supply chains in line with the Sustainable Development Scenario (SDS) objectives [17]. Currently, biofuel output in the United States and European Union lags the pace required to meet the SDS benchmarks for 2030 [18]. Compounding the issue, many nations are witnessing a decline in both absolute biofuel consumption and its share relative to fossil fuel use. This trend is largely attributed to advancements in vehicle fuel efficiency, which have led to reduced overall transport fuel demand. Without a broader deployment of drop-in biofuels, this downward trajectory in consumption is likely to continue.

While biofuel production in countries like Brazil and India is projected to rise, the current pace remains insufficient to meet the SDS volume targets by 2030 without more targeted and effective interventions. Brazil marked a significant milestone in 2019, achieving record levels of ethanol and biodiesel output. The country currently integrates over 20% ethanol into its fuel mix and is gradually increasing its biodiesel blending mandate from 11% to 15% [17]. India is

making strides toward its 2030 SDS commitments through the implementation of its National Policy on Biofuels (NPB) 2018, which authorizes the use of second-generation feedstocks, such as lignocellulosic biomass, agricultural residues, and surplus food grains for ethanol production. To bolster this effort, the Indian government has introduced financial incentives to expand biofuel production infrastructure. Additionally, countries within the Association of Southeast Asian Nations (ASEAN), alongside China, are intensifying biofuel output to enhance energy security and contribute meaningfully to SDS-aligned goals by 2030 [19].

Globally, countries are intensifying efforts to meet SDS targets by expanding biofuel production, mandating higher blending ratios in transportation fuels, and promoting increased consumption in alignment with SDS directives [3]. However, the ability to scale biofuel output depends on several interdependent factors: the sustained availability and quality of feedstocks, the biochemical and physical characteristics of biomass, the maturity and scalability of emerging production technologies, and the demonstrated viability of existing technological pathways. Crucially, the success of advanced biofuel initiatives also hinges on strong policy frameworks and institutional support to enable project implementation and long-term adoption.

3. Production Processes and Challenges

3.1. Production of Biogas from Waste Vegetable Feedstocks

Although biogas is classified as a renewable energy source, it is not strictly considered green because it is not carbon-neutral. Typically, its production from biomass waste relies on both chemical and biochemical conversion technologies [20]. Among these, anaerobic digestion stands out as one of the most effective and widely endorsed methods for generating biogas from food-based waste streams [21, 22]. This process entails the microbial decomposition of organic material in an anaerobic or oxygen-free environment that ultimately yields biogas, which can be harnessed for electricity generation, cooking applications, and as a transport fuel. Beyond its functional utility, anaerobic digestion offers several notable benefits, including valorization of organic waste, enhanced energy autonomy, and meaningful contributions to environmental preservation. However, countries like the USA and certain European nations have made significant advancements in biogas [23]. In countries such as China and others in Asia, the development of the biogas industry has been minimal since the 1990s [24].

Lignocellulosic biomass, such as FVW, presents a significant bottleneck in biogas production due to the presence of lignin, which impedes effective hydrolysis and inhibits the colonization of facultative microbes, both bacterial and fungal, during fermentation. This structural barrier substantially reduces the potential yield of methane [25, 26]. To overcome this limitation, pre-treatment processes are essential for converting the cellulose and hemicellulose

fractions into enzyme-accessible forms. Such biochemical pre-treatment not only prevents process disruptions but also enhances the efficiency of anaerobic digestion, ultimately leading to improved biogas output [27]. Hence, effective pre-treatment of lignocellulosic FVW is critical to breaking down complex polysaccharide structures and facilitating enzymatic biodegradation during downstream processing.

Various pre-treatment techniques that include chemical, biological, physical, thermophysical, and thermochemical approaches have been employed to enhance methane production from lignocellulosic biomass wastes [28]. These methods generally improve substrate porosity and increase the accessibility of cellulose and hemicellulose to enzymatic action. However, they can also trigger the formation of inhibitory byproducts, which adversely affect the activity of anaerobic microbial communities [29]. As such, while pre-treatment is critical for improving bioconversion efficiency, it presents a trade-off; excessive or improperly managed application may inadvertently suppress methane yield due to the accumulation of toxic intermediates.

Sequencing batch reactors have gained prominence over conventional single-stage anaerobic digesters, primarily due to their superior retention and elimination of solids and the need for settling phases [30]. One of the defining advantages of two-stage bioreactors lies in their operational flexibility in adjusting hydraulic retention time. This has encouraged the use of sequentially configured bioreactors dedicated separately to acetogenesis and methanogenesis, thereby negating the requirement for intermediate clarifiers. During the anaerobic digestion process, acidogenic microorganisms actively produce carbon dioxide, hydrogen, and acetate as metabolic intermediates [31]. These byproducts, notably hydrogen and acetate, serve as substrates for methanogenic archaea, which convert them into methane and water. However, under high organic loading conditions, the rapid accumulation of hydrogen can stimulate acidogenic activity, increasing metabolic throughput. If methanogens fail to match this pace, due to enzymatic limitations or environmental stress, methane production can stall, effectively halting the overall digestion process [32].

Rapid acidification and elevated production of volatile fatty acids are primarily attributed to the high biodegradability of vegetable waste, which in turn inhibits the activity of methanogenic microorganisms [33]. To counteract such inhibitory effects and improve overall digestion efficiency, various process enhancements have been explored, most notably, the use of co-substrates. Co-digestion offers a strategic advantage by diluting toxic intermediates and balancing nutrient profiles, particularly in cases where vegetable waste lacks essential elements like nitrogen and phosphorus [34]. Supporting this approach, studies have demonstrated that incorporating activated sludge into the co-digestion of FVW within a two-stage system can significantly

enhance methane yield, reaching concentrations as high as 68% [35-37].

3.2. Production of Bioethanol from Waste Vegetable Feedstock

Bioethanol production from FVW involves a multistep process that includes the pre-treatment of the lignocellulosic fraction, enzymatic depolymerization, and microbial fermentation of the resulting hydrolysate into ethanol. A variety of pre-treatment techniques have been shown to significantly enhance ethanol yield, including physical disruption, chemical treatment, hydrothermal steam explosion, ammonia fiber expansion, hot water exposure, and ozonolysis [38]. Before fermentation, this conversion of the complex polymolecular carbohydrate structure into simple sugars can be achieved either under acidic or alkaline conditions, or through enzymatic hydrolysis, allowing the efficient breakdown of the lignocellulosic structure of FVW into accessible monosaccharides [39].

Pretreatment is an important step in the bioethanol production from FVW because it maximizes cellulose hydrolysis. Following adequate pre-treatment, glucose yields have been reported to be over 90% when acidic or enzymatic conditions are employed. Unmodified biomass, on the other hand, gives direct hydrolysis yields below 20% [40]. Of the different pretreatment approaches, dilute sulfuric acid-based methods have been one of the more established methods to allow enzymatic hydrolysis of lignocellulosic biomass in bioethanol production [41]. Acid hydrolysis itself is one of the oldest known methods for converting cellulose-based materials and is generally classified into two methods: concentrated acid hydrolysis and dilute acid hydrolysis [42]. Dilute acid processing has proven to be an effective method for removing hemicellulose, especially when adapted for continuous processing under high temperatures and pressures, where short reaction times can successfully hydrolyze hemicellulose.

In the acid dilution process, a 1% sulfuric acid solution is typically introduced into a reactor operating at around 215 °C [43]. The efficiency of biomass conversion to fermentable sugars via this method is, however, limited, usually around 50%. This technique has the drawback of achieving glucose yields of no more than 70%. Concentrated acid hydrolysis, on the other hand, works under less severe temperature and pressure conditions but requires much longer reaction times. Though this process takes longer, it allows for good, efficient, and complete degradation of glucose or hemicellulose into C5 sugar products with little product degradation. Almost all acid methods are favored due to their rapidity and cost efficiency, but they tend to destroy the structural integrity of the target sugars. For this reason, chemical hydrolysis is a less sophisticated, non-selective method than enzymatic hydrolysis. This brings several advantages, such as high sugar yields, moderate temperature

for the reaction, and a low yield of inhibitory by-products, due to the specificity of the enzymes that partake in cellulose depolymerization [44].

Enzymatic hydrolysis also has the disadvantage of slow reaction kinetics as well as high implementation cost, which still prevents it from being more widely used industrially. There are also methods requiring mechanical disruption of the biomass prior to hydrolysis that can lead to unwanted inefficiencies and lower the effective hydrolytic activity in terms of duration [45]. Thus, a suitable pretreatment should be selected to eliminate lignin and hemicellulose to improve the capabilities of enzymatic conversion processes using lignocellulosic biomass [46]. A universal procedure for the best enzyme-substrate ratio for effective hemicellulose removal from FVW is still lacking. The absence of agreement creates yet another difficulty; thus, the efficient conversion of FVW into bioethanol is a relevant, unresolved, technical matter.

The lack of knowledge concerning important process parameters, such as the concentration of sulfuric acid, the time for saturation during the pre-treatment, and the ratio of enzyme to substrate, represents one of the main obstacles for the successful conversion of FVW to bioethanol. These factors contribute to significant uncertainty and variability, making FVW a less desirable candidate for clean, renewable energy generation. Misapplications of the chemical or enzymatic process can drastically reduce ethanol production, especially since the chemical content of FVW varies greatly based on the conditions of the pre-treatment process, such as the concentration and time [47]. As a result, there are no standardized protocols that still represent a relevant technical challenge for the efficient use and conversion of FVW into bioethanol.

A significant limitation of the Simultaneous Saccharification and Fermentation (SSF) process arises from the mismatch in optimal operating temperatures: hydrolytic enzymes used for biomass breakdown function most efficiently between 45°C and 50°C, whereas fermentative microbes typically perform best around 30°C [48]. This disparity poses a substantial technical challenge in process integration.

Beyond this, bioethanol faces several inherent drawbacks that hinder its broader adoption. These include its comparatively lower energy density relative to gasoline, a propensity to absorb moisture that led to hydrolytic degradation, corrosive effects on metal engine components and storage infrastructure, poor volatility at low temperatures that can delay engine ignition, and susceptibility to enzymatic degradation during fermentation [49].

Collectively, these factors have constrained the large-scale commercial viability of Bioethanol. Compounding the issue are additional barriers within the Bioconversion pathway. These include the need to reduce lignin content in biomass genetically, the development of scalable and efficient pre-treatment technologies for lignocellulosic feedstocks, and the lack of a unified process for the concurrent fermentation of pentose to engineer microbial strains with heightened ethanol tolerance. Despite these challenges, bioethanol remains a promising bioenergy alternative, produced via fermentation from a wide array of feedstocks, including edible starches (e.g., corn, wheat, barley), sugarcane, kernels, and increasingly, from lignocellulosic agricultural residues such as FVW. Representative examples of bioethanol production using FVW are summarized in Table 1.

Table 1. An outline of the methods applied, the resulting yields, and the challenges encountered in the bioethanol production process using FVW [37]

S. No	Feedstocks	Advantages	Challenges	Bioenergy Type	Conversion Process	Reported Yield / Conversion Efficiency
1	Grapes, pomegranates, and orange peels	Readily available at no acquisition cost	Limited economic viability	Bioethanol	Fermentation	Ethanol yields of 15.13%, 19.1%, and 5.89% respectively
2	Pineapple, banana, plantain peels	No conflict with food chain resources	High energy and processing costs	Bioethanol	Fermentation	Ethanol yields of 8.34%, 7.45%, and 3.98% respectively
3	Papaya peels	High sugar levels make it a promising substrate	Requires costly hydrolysis and saccharification; poor economics	Bioethanol	Fermentation	Yield reported at 0.51%

4	Orange, banana, potato, pea residues	Contributes to waste minimization and environmental benefits	Not feasible for industrial scale; high operational cost	Bioethanol	Fermentation	Ethanol yields of 3.8%, 3.0%, 5.5%, 3.1%, and 1.9% respectively
5	Mango, banana, papaya peels	Low-cost feedstock, lowers GHG footprint, aids waste valorization	High lignin fractions hinder fermentation	Bioethanol	Fermentation	High ethanol yields: 95.05%, 96.11%, and 95.49% respectively
6	Pineapple, banana, orange, pea peels	Economical, widely accessible, and effective substrate	Yield insufficient for commercial scale-up	Bioethanol	Fermentation	Reported yields of 8.34%, 7.45%, 3.98%, and 2.58% respectively
7	Indian blueberry, apple, and grape residues	Renewable, biodegradable, and eco-friendly	Low yield, inadequate for large-scale applications	Bioethanol	Fermentation	Yields of 6.5%, 4.5%, and 5.2% respectively
8	Pineapple, watermelon peels	Rich sugar fraction enhances fermentation	Fermentation efficiency is strongly influenced by pH and microbial conditions.	Bioethanol	Fermentation	Ethanol yields of 11.11% and 10.19% respectively
9	Palm fruit waste	Good conversion efficiency and environmental benefits	Susceptible to spoilage and contamination	Bioethanol	Fermentation	Ethanol yield of ~25%

3.3. Production of Biodiesel from Waste Vegetable Feedstock

Biodiesel, a renewable form of bioenergy, is typically synthesized via transesterification. This chemical reaction converts edible or non-edible oils with an alcohol (Commonly Methanol or Ethanol) in the presence of a catalyst. This process yields fatty acid methyl esters (Biodiesel) and Glycerol as a byproduct. One of the primary objectives of transesterification is to reduce the inherent viscosity of the feedstock oils, thereby enhancing fuel properties and engine compatibility [50]. As illustrated in Figure 1, the resulting biodiesel is regarded as environmentally benign, owing to its low toxicity and significantly reduced carbon dioxide emissions compared to conventional fossil fuels. Among the various techniques available for biodiesel production, methods such as pyrolysis, micro-emulsification, blending with petroleum diesel, esterification, and transesterification are the most widely adopted [51].

The efficiency and outcome of the transesterification process are strongly governed by several key factors, including the type of catalyst employed, reaction temperature,

Free Fatty Acid (FFA) content of the feedstock, and the alcohol-to-oil molar ratio [52]. Catalysts play a critical role in accelerating reaction kinetics and enhancing product yield by shifting the equilibrium toward ester formation, given the reversible nature of the reaction [53]. Optimization of these parameters is particularly impactful. For instance, a study achieved a remarkable 99% biodiesel yield within just 50 minutes by employing ultrasonic irradiation at 20 kHz to catalyze the transesterification of canola oil [54]. Despite these advancements, the selection of reaction conditions, such as the type of solvent, catalyst, and operating temperature, continues to be a decisive factor. Ultimately, biodiesel production is intricately linked to the nature and composition of the chosen feedstock [55].

A significant barrier to the widespread commercialization of biodiesel lies in the high cost associated with acquiring suitable feedstocks. This economic constraint has prompted many countries to explore cost-effective, locally available alternatives to curb production expenses and support domestic resource utilization. By leveraging indigenous raw materials, nations not only reduce dependency on imported inputs but

also foster the growth of local agricultural and industrial sectors. In Europe, rapeseed and sunflower oil have emerged as the predominant feedstocks, whereas the United States

primarily utilizes soybean oil. In Southeast Asia, palm oil remains the feedstock of choice for biodiesel production [56].

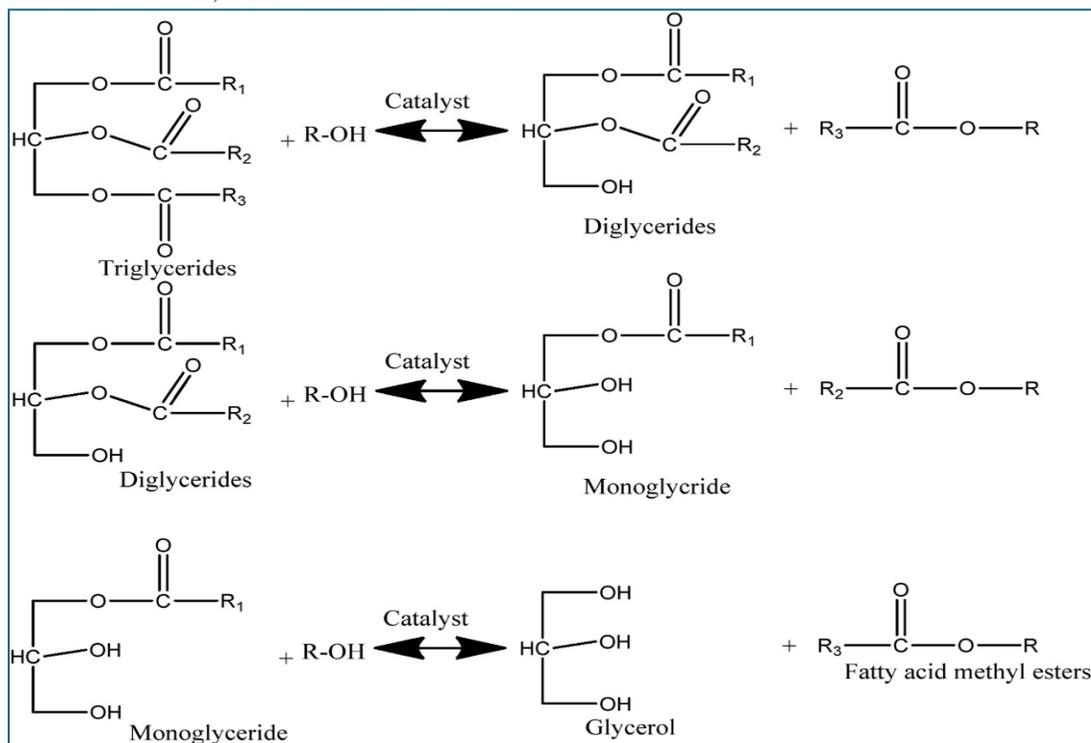


Fig. 1 Basic scheme of biodiesel synthesis showing triglyceride breakdown to diglycerides and monoglycerides via alcohol and catalyst action

While the influence of biodiesel on global commodity prices remains relatively modest, there has been a notable shift in feedstock selection from edible to non-edible sources to reduce production costs. The ongoing food-versus-fuel debate, stemming from the use of food crops in energy generation, has catalyzed the exploration of alternative feedstocks such as non-edible oil-bearing plants, microalgae, and even sludge-derived waste materials [57]. These strategies are not only aimed at lowering the cost of raw materials, which represent a significant fraction of overall biodiesel production expenses, but also at enhancing the long-term sustainability of the industry [58]. In this context, the selection of feedstock is predominantly guided by two critical criteria: local availability and economic feasibility [59]. Prioritizing regionally sourced, low-cost inputs ensures a more resilient and cost-efficient biodiesel production process.

In the pursuit of economically viable and locally sourced feedstocks, biomass wastes with high lipid content have emerged as promising candidates for biodiesel production. Among various food categories, fruits and vegetables account for the highest losses and waste globally, according to FAO estimates. Repurposing this waste into biodiesel presents a meaningful opportunity to support the sustainable generation of clean, renewable fuels [60]. Within this context, FVW stand out as a valuable bioresource, owing to their significant oil

content and widespread availability. The extraction of these lipids, critical to biodiesel synthesis, can be accomplished through either chemical or mechanical means, depending on the process requirements and feedstock characteristics [61, 62].

Vegetable waste-derived oil from castor seeds was processed using a non-ionic base-catalyzed transesterification approach employing TBD as the catalyst. Remarkably, a single mole of TBD yielded 90% alkyl esters within just one hour of reaction time, without the undesirable formation of soap in conventional base-catalyzed methods [63]. Further experimentation revealed that increasing the catalyst loading to 2 and 3 moles resulted in slightly higher ester yields of 91% and 93%, respectively. These findings underscore the efficiency of TBD as a catalyst and highlight the practical potential of abundantly available vegetable waste, such as castor seed residue, as a promising feedstock for sustainable biodiesel production.

Biodiesel production from FVW typically involves the transesterification of extracted oils with simple alcohols, either in the presence or absence of a catalyst. However, the overall efficiency of this process remains highly dependent on several interrelated parameters, including reaction temperature, the standardized alcohol-to-oil ratio, catalyst

selection, the choice of solvent tailored to specific feedstocks, mixing intensity, and the purity of the reactants. These variables collectively present a considerable challenge in optimizing biodiesel synthesis from biomass wastes like FVW. As such, there is a pressing need for further research to develop practical, cost-effective strategies that can enhance yield, improve process reliability, and support the long-term sustainability of biodiesel production from these unconventional feedstocks.

The choice of catalyst is also very important for a sustainable and efficient process when producing biodiesel via transesterification. Homogeneous, heterogeneous, and enzymatic catalysts have all been widely utilized for this transformation [64]. Homogeneous base catalysts are among these, while also being favored because reaction rates are relatively faster than those of acid catalysts [65]. Bridjesh et al., for example, point out that Sodium Hydroxide (NaOH) and Potassium Hydroxide (KOH) are the most used alkaline catalysts at an industrial scale for biodiesel production [52]. They are also popular because they can be very active catalysts in mild reactions, especially at lower temperatures. Plus, base-catalyzed transesterification processes have also gained popularity due to the low cost of operation, short time of reaction, and reliability of the process under ambient to quasi-ambient conditions as well [66].

Although base catalysts have important advantages, their use is limited because they only work if the feedstock has a low content of fatty acids. These catalysts have been found to work only at FFA concentrations lower than 0.5 wt.% in pure vegetable oil and thus cannot be applied to oils with higher FFA content [67]. Also, the higher tendency to form soap when oils containing free fatty acids greater than 2 wt.% are used, which is one of the most important disadvantages of base-catalyzed transesterification, and will considerably impede the separation of the phases and therefore reduce biodiesel yield [68, 69].

Although heterogeneous catalysts provide some operational benefits, they still require high reaction temperature, pressure, and concentration of reagents, which increases the production cost overall. Heterogeneous catalysts, while offering these operational advantages, often require high reaction temperatures, pressures, and concentrations of reagents, thus increasing the overall cost of production. Other drawbacks are product contamination by leaching of the catalysts, complicated and expensive synthesis routes, low tolerance to Free Fatty Acids (FFA), and metal reactor parts might corrode [70]. Alternatively, there has been some research into the use of alternative chemical catalysts, particularly enzyme-based catalysts. Nevertheless, enzyme systems represent a great potential but have also important drawbacks, including high production costs, difficulties in recovering and reuse, limited stability in operational conditions, and being prone to deactivation [71]. In addition,

other limitations of biodiesel production via enzymatic processes are long reaction times, loss of catalytic activity over time, generation of side-products, and great susceptibility to feedstock with high free fatty acid content [72]. Considering these barriers, there is an urgent need to develop and optimize non-catalytic process technologies capable of achieving high-yield biodiesel production from biomass wastes such as Waste Vegetable Oil (WVO), thereby circumventing the shortcomings associated with both chemical and biological catalysts.

3.4. Production of Biohydrogen from Waste Vegetable Feedstock

Biohydrogen stands out as a promising carbon-free energy carrier, recognized for its minimal emissions, negligible environmental footprint, and wide-ranging applicability across energy sectors. This clean form of bioenergy is primarily generated through fermentative pathways, notably photo-fermentation and dark fermentation [73]. Light-driven processes, such as direct and indirect biophotolysis, typically operate under aerobic conditions and depend heavily on sustained illumination. In photo-fermentation, photosynthetic microorganisms capable of utilizing light as their energy source convert organic substrates like fatty acids into hydrogen gas. This mechanism enables the generation of considerable volumes of biohydrogen [74]. However, the scalability of such systems remains constrained by significant limitations, including the high cost of electrode materials and the intensive light energy requirements, both of which pose barriers to broader commercial deployment [75].

In contrast, dark fermentation proceeds under strictly anaerobic conditions and offers several compelling advantages over photo-fermentation. Its independence from light energy, minimal reliance on external power inputs, faster reaction kinetics, and comparatively lower operational costs make it an attractive and potentially more sustainable biohydrogen production route [76]. These attributes position dark fermentation as a particularly viable option for processing complex organic waste materials. FVW have gained growing research interest as a substrate for biohydrogen generation, owing to their high carbohydrate content and naturally low nitrogen levels. These characteristics align well with the metabolic requirements of hydrogen-producing microbial systems.

As organic wastes, FVW represent a very promising substrate among others because of their high organic loading, hydrolysis, and biodegradability speed. Thus, they possess a high potential to produce biohydrogen, higher than many other conventional waste materials [77]. In dark fermentation, FVW's complex macromolecular compounds are disintegrated by microbial metabolic pathways into volatile organic acids, alcohols, and simple sugars that serve as precursors to hydrogen production. Such a process is

advantageous, especially because FVW has a high carbohydrate content, varying between 30%-70%, which is significantly higher than that from substrates like sewage sludge or animal waste, whose carbohydrate content is below 10% [78]. FVWs, therefore, constitute a beneficial and promising feedstock for the sustainable production of hydrogen.

Photosynthetic and fermentative microorganisms play a notable role in biohydrogen production [79]. Concurrently, it is well established that dark fermentation proceeds via two key anaerobic metabolic stages: acidogenesis and acetogenesis. These pathways are primarily facilitated by bacterial strains [80]. In one study, FVW were utilized as a substrate for hydrogen production through dark fermentation, achieving an optimal yield of 52 cm³/gVS when operated at an Organic Loading Rate (OLR) of 17 m³/gVS. The authors attributed the process stability to the substantial lactic acid production by the microbial community, which helped maintain favorable fermentation conditions throughout the experiment.

In a separate study, fermentation was employed to generate biohydrogen from FVW, predominantly composed of vegetable matter [81]. Conducted at laboratory scale, the experiment involved mixing the feedstock with anaerobic sewage and incubating the mixture at 37 °C for 31 days. The process yielded a maximum hydrogen output of 42.00 ± 1.76 mL, representing an increase of approximately 90%–100% compared to. Figure 2 illustrates the fermentation pathway in producing Biohydrogen, incorporating vermicompost as a microbial inoculum [82]. Batch fermentation was carried out at 35 °C under mesophilic conditions. In this setup, substrates underwent mild heat pre-treatment, which served to inactivate native microbiota present in the FVW. This pre-treatment step significantly enhanced hydrogen generation relative to the untreated control. By the conclusion of the experiment, the system achieved a hydrogen yield of 63.0 mL/g VS, a volumetric production rate of 372.6 mL/L/day, and a biodegradation efficiency of 50% as measured by BOD5 reduction.

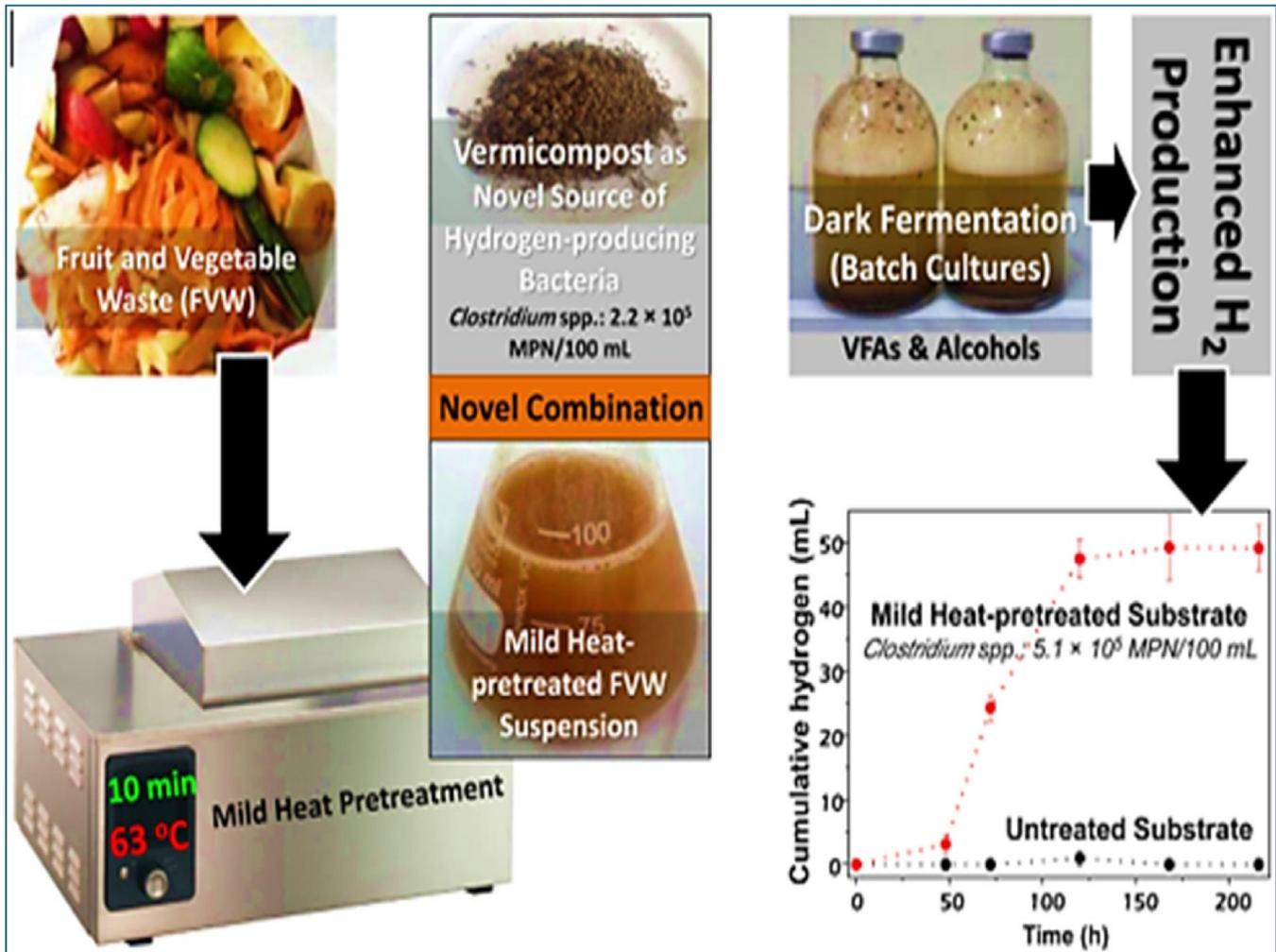


Fig. 2 Schematic representation of fermentative biohydrogen generation employing a novel approach that integrates vermicompost as the inoculum with mild heat-pretreated Fruit and Vegetable Waste [82]

A significant challenge in utilizing these substrates lies in their high lignocellulosic content, which is inherently resistant to natural degradation. Plant-derived waste materials typically consist of complex polymeric structures, where cellulose and hemicellulose are intricately bound to lignin, forming a rigid matrix.

This tight association hampers enzymatic access and complicates the breakdown process. Moreover, the monosaccharides embedded within these lignocellulosic networks are often inaccessible for fermentation, as the lignin acts as a physical barrier and exhibits resistance to environmental factors such as temperature and microbial attack [83].

A growing body of research supports the beneficial role of pre-treatment in enhancing biohydrogen yields. For example, elevating the heating temperature from 60 °C to 90 °C has been shown to improve hydrogen production efficiency significantly [37]. Beyond pre-treatment, alternative strategies such as microbial electrolysis cells and the integration of methane production pathways have also been explored to optimize hydrogen output further. Among the various approaches, dark fermentation is widely recognized as one of the most promising and practical methods for H₂ generation. However, a key barrier to its industrial-scale implementation lies in its limited hydrogen yield.

As a result of microbial metabolic activity, over 70% of the carbon and hydrogen content is often diverted into by-products rather than being converted directly into hydrogen gas. Despite this limitation, the strategy has been effectively applied to enhance both conventional dark fermentation and single-stage systems, aiming to improve overall hydrogen production efficiency [84].

Notably, this approach has been more commonly implemented in the treatment of food-processing wastewater than in the context of FVW [85]. Nevertheless, recent findings demonstrate that the simultaneous generation of hydrogen and methane from FVW can markedly elevate the bioenergy conversion efficiency, raising hydrogen recovery rates from as low as 8% to as high as 78% [86].

A fermentation system is shown to effectively maximize the co-production of hydrogen and methane, yielding approximately 41 mL H₂/g COD and 310 mL CH₄/g COD, respectively [87]. These suggest that nearly 71% of the total energy content present in food vegetable wastes can be harnessed, with hydrogen contributing a modest 3% and methane constituting the bulk of the recovered energy. This strategy offers a sustainable alternative to conventional sequential methane fermentation and has demonstrated the added benefit of reducing the need for alkaline agents in pH regulation by nearly 40–50% [88].

Taken together, these findings underscore that FVW holds considerable promise as a feedstock for hydrogen production via dark fermentation, often outperforming other organic solid waste substrates.

Despite its promise, the widespread application of this process technology is hindered by several critical challenges. Chief among them are the low rates of biodegradation, the absence of an optimized sterilization protocol, and the lack of a universally accepted pre-treatment method. In many cases, excessive pre-treatment can actually reduce overall yields, making the process economically unattractive due to high operational costs coupled with diminished output [89].

Additional obstacles include the complexities involved in establishing optimal co-culture conditions, the difficulty in selecting appropriate microbial strains for dark fermentation, and the lack of effective strategies to suppress hydrogen-consuming bacteria.

Moreover, bioreactor design remains a crucial yet under-addressed issue affecting both photo and dark fermentation systems. For instance, photo-fermentation requires reactors with high surface-to-volume ratios, which significantly increases reliance on light and, by extension, operational expenses.

The photobiological production of hydrogen using microalgae derived from FVW presents a viable renewable energy pathway, primarily due to the innate capacity of these microorganisms to generate hydrogen gas under illumination, as illustrated in Figure 3. This process begins with the photosynthetic splitting of water molecules by microalgae, yielding oxygen (O₂) and protons (H⁺). Under anaerobic conditions, the protons are subsequently reduced to molecular hydrogen (H₂) via the catalytic action of hydrogenase enzymes [37].

A critical bottleneck, however, arises during photosynthesis: the oxygen produced concurrently can rapidly inhibit hydrogenase activity, thereby interrupting hydrogen generation. This underscores the necessity of maintaining strictly anaerobic conditions for successful H₂ production by microalgal cultures [90].

Two principal photosynthetic routes have been identified for microalgal hydrogen production. The first involves the concurrent generation of O₂ and H₂ in the presence of light, while the second relies on hydrogenase enzymes to catalyze proton reduction using electrons derived from water oxidation.

Despite its promise, this technology remains constrained by low photoconversion efficiency and the still-developing state of technological expertise required to optimize biohydrogen production at scale [91].

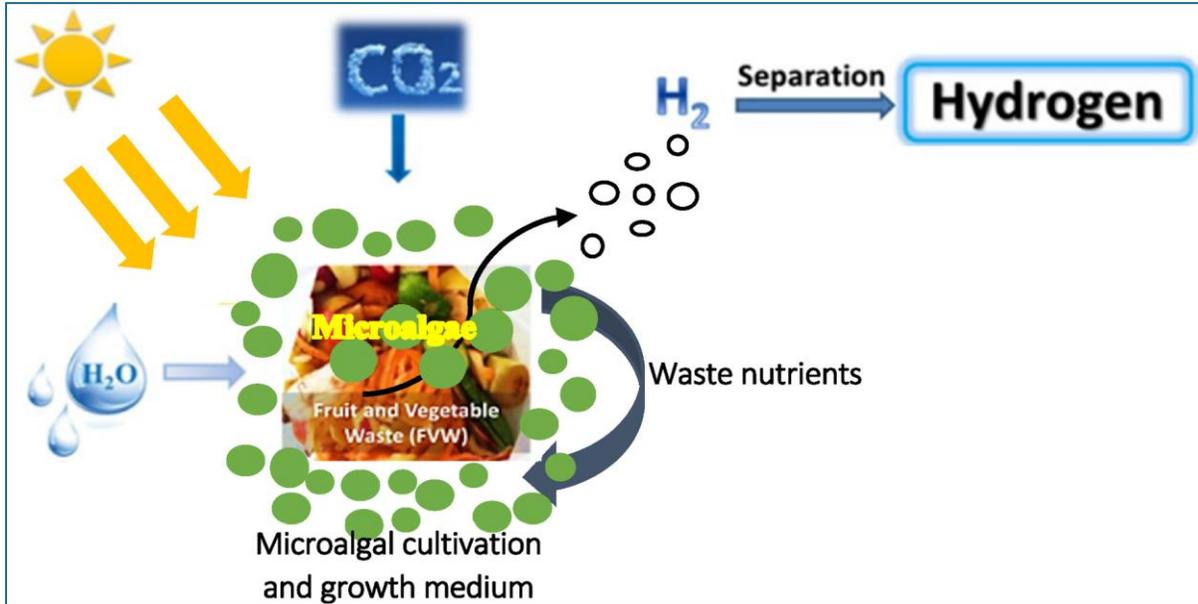


Fig. 3 Schematic depiction of a possible photobiological hydrogen production pathway utilizing microalgae cultivated from FVW [37]

4. The Use of Biofuel and Sustainability Goals

4.1. Environment and Climate Change Perspectives and the State of the Atmosphere

The possibility of biofuels to mitigate the increasing greenhouse gas emissions from the automobile sector makes them highly appealing [92]. According to what they found, the researchers discovered that switching to biofuels from fossil fuels could significantly lower greenhouse gas emissions and pollution and offer a beneficial solution for Climate Change Mitigation and adaptation.

Automotive fuel combustion releases Nitrogen Oxides (NO_x), Particulate Matter (PM), Unburned Hydrocarbons (HCs), Sulphur Dioxide (SO₂), and Carbon Monoxide (CO), which degrade the environment. Additionally, NO_x and HCs can generate other pollutants, specifically the ozone layer, the main component of smog formed by photosynthesis. Furthermore, breathing in CO, especially particulate matter, poses a serious health risk [93].

4.2. The Use of Ethanol Blends to Control Air Pollution

By increasing fuel combustion and improving oxygen content, ethanol blends with gasoline to enhance air quality, reduce pollutant emissions, and make it a safer fuel for transportation. Ethanol blends, particularly E10, E15, E22, and E100, were the focus of emission investigations [94]. According to Table 2, this investigation validates notable reductions in air pollution gases.

Overall pollutant emissions are shown in Table 3, with E15 blends significantly decreasing PM by 41%, NO_x by 5%, and CO by 27%. The Karnataka State Transport Corporation bus fleet in India participated in a test using E 7.7 ethanol-blended gasoline [96].

Table 2. Reduction of emissions of air pollutants with different percentages of ethanol blending [95]

Pollutant	Emission (%)		Emission (g/km)	
	E10	E15	E22	E100
Particulate matter	27	41	0.08	0.02
Carbon monoxide	20	27	0.76	0.65
Unburned HC	-	-	0.004	0.02
NO _x	4	5	0.45	0.34
Sulphur dioxide	-	-	0.064	0

Table 3. Trends in pollutant emission mitigation at different biodiesel blending ratios [96]

Pollutant	Emissions Reduction (%)			Emission (g/km)	
	Diesel	B20	B100	B15	B10
Unburned HC	0.37	-30	-93	0.16	0.22
NO _x	0.79	2	13	0.89	0.83
Particulate matter	0.129	-22	-30	0.08	0.093
Carbon monoxide	0.77	-20	-50	0.62	0.65
Sulphur dioxide	-	-20	-100	-	-

4.3. The Use of Biodiesel Blends to Control Air Pollution

Biodiesel powering for diesel engines has demonstrated promising outcomes in lowering emission levels of harmful gases. Blending biodiesel with diesel results in an approximately 11% oxygen content, improving combustion and lowering PM and CO. Biodiesel also does not add sulfur to the air and is extremely biodegradable. As indicated in

Table 3, the percentage-pollutant emission and g/km concentrations of the biodiesel fuel blends B100, B20, B10, and B15 varied. 10%, 15%, and 20% biodiesel with 90%, 85%, and 80% gasoline make up the fuel mixtures labelled B10, B15, and B20. E100. According to EPA's 2010 analysis, blending biodiesel with soy oil and waste grease reduced greenhouse gas emissions by 57% and 86%, compared to fossil fuel [96]. Another study found that blending biodiesel dramatically reduced unburned HC, CO, SO_x, and PM 2.5. Nonetheless, a small increase in NO_x has been noted (Table 3).

4.4. Views on Biofuels and Climate Change

By capturing CO₂ directly from the environment through photosynthesis, biomass used to make biofuels can mitigate this crucial greenhouse gas. Changes in land use have an impact on GHG emissions either directly or indirectly. For example, switchgrass biomass saves 8.6 tons of CO₂/ha/year, whereas ethanol made from maize grain can save 1.8 tons. About 300 tons/ha can be released when grassland and forest areas are converted to biofuel crops [97, 98]. Table 4 displays these data points.

A wide range of approaches to control greenhouse gas emissions has been under consideration. Across the world, several policy efforts have also been established. For instance, Jayant et al. suggested two strategies to lower carbon emissions. Life cycle approach, because, unlike fossil fuels, energy crops and biofuels enter and exit the carbon pool from the atmospheric pool, without affecting the overall C-pool. The second strategy is biofuel blends to substitute or transition from fossil fuels. Burning non-renewable fuels is typically a part of producing biofuels [99].

In comparison to gasoline, it is observed that the impacts of biodiesel (2 G) and ethanol (1 G) derived from sugarcane reduced greenhouse gas emissions by approximately 70%–100% [100, 101]. Nonetheless, higher GHG emissions are associated with larger fertilizer dosages during crop production. GHG levels significantly differ in crop, locales, feedstock production techniques, transformation technologies, and usage [101].

Compared to fossil fuels, research has shown that producing 1-G and 2-G biofuels might decrease greenhouse gas emissions by 20%-60% [102]. Since plant photosynthesis absorbs the CO₂ released during combustion, biofuels have near-zero emissions. Research has shown that using 1 G-biofuels reduces CO₂ emissions by 20% to 60% compared to using fossil fuels. 2. G-biofuels may lower GHG CO₂ by 70% to 90% compared to fossil fuels. According to estimates, 2 G-biofuels made from cellulosic material can store more carbon than one G-biofuel made from sugars or starch [103, 104]. When using Jatropha biodiesel instead of fossil fuel, GHG emissions can be reduced by 8 to 88%.

Table 4 presents selected LCA studies on biofuels along with their projected Greenhouse Gas (GHG) reductions compared to conventional fossil fuels. Microalgae can potentially reduce climate change by efficiently converting photons into photosynthetic energy, according to [105, 106]. Additionally, it is possible to create algal biomass all year-round. The generation of algae-based biodiesel is more environmentally friendly and sustainable than other bioenergy sources [107]. The methods by which microalgae aid in Capturing And Storing Carbon (CCS) were revealed by [108, 109].

Table 4. Representative LCA studies on biofuels and their projected GHG reduction potential in comparison with fossil fuels [105]

Biofuels	Feedstock	Reference Fuel Type	GHG Balance	Country
Bioethanol	Switchgrass - corn stover	Low-sulfur gasoline	65% lower GHG	Canada
	Switchgrass	Coal	114% GHG saving	USA
	Corn-soybean	Coal	38-41% GHG saving	USA
	Blue-green algae	Gasoline	67-87% reductions	USA
Biodiesel	Jatropha	Diesel	72% GHG savings	Mali
	Microalgae	Diesel	About 80% lower GWP	UK
	Rapeseed	Diesel	56% GHG savings	Italy
	Microalgae wastewater sludge	-	GHG emissions reductions	USA
Biomass to Liquid (BtL biofuels)	Microalgae	Coal thermal plant	GHG emissions reductions	Japan
	Rapeseed, palm, jatropha oil	Diesel	GWP reduced by half	USA
	Camelina sativa L.	Petroleum jet	23.34% less GHG	USA
Biomethane	Grass	Diesel	54-75% GHG savings	Ireland
	Grass	Diesel	85% GHG savings	Ireland
Biohydrogen	Potato peels	Defined	GHG reductions	USA
	Biomass gasification	Diesel	GHG reductions	Turkey
	Food waste and wheat feed	Diesel	GHG reductions	UK
	Microalgae	Electricity	GHG reductions	Portugal
	Algal biomass	Petroleum-based fuels	GHG reductions	Canada

4.5. Carbon Reduction Potential and Energy Balance of Biofuels

Its carbon balance and energy efficiency determine any biofuel's potential. According to CII [CII, 2010], biofuel is classified as renewable if its Energy Ratio (NER), which measures the energy returned on energy spent, is greater than 1. The difference between the total energy spent during fuel production and the energy values of the fuel that is produced is known as the net energy balance, or NEB. When the system produces more energy than it consumes, the NEB is positive, which is regarded as a crucial condition for biofuel sustainability. The difference between carbon emissions from inputs and outputs is known as the net carbon balance, or NCB. Using biofuel instead of fossil fuels, the net amount of GHG emissions saved is measured using C-emission reduction [96].

When sorghum stalks were pretreated with diluted acid for sugar recovery, the corresponding NEB, NCB, and percentage of C-reduction were 42.45%, 17.5 GJ/kl, and 0.76 tCO₂e/kg. The NEB, NCB, and C-reduction percentages of ethanol made from sorghum and pearl millet feedstock sugar were 16.8 GJ/kl, 0.96 tCO₂e/kl, and 50.69%, respectively. According to these results, ethanol made from biomass is a fuel that emits no carbon.

Advanced biofuels that reduce greenhouse gas emissions by at least 50% relative to fossil fuels are categorized by the US Environmental Protection Agency and the California State Air Resources Board. Table 5 indicates the balance of selected biofuels' net energy and carbon (C).

Table 5. Energy balance and carbon footprint of selected biofuels [96]

Liquid Biofuels	Feedstock used	NEB (GJ/kl)	C-reduction	NER	NCB (tCO ₂ e/kl)
Ethanol	Sweet Sorghum	21.6	86%	7.1	-1.4
	Molasses	19.1	75%	4.6	-1.1
	Rice straw	22.8	68%	3.3	-1.6
	Sugarcane bagasse	25.4	70%	4.4	-1.7
Biodiesel	Jatropha-SVO	66.7	50%	4.4	-4.5
	Jatropha-Transester	63.8	30%	53.4	-4

On the other hand, ethanol is the most important factor in the transportation sector, and it helps reduce carbon-containing emissions from gasoline consumption. The benefits of biodiesel and its significant potential to reduce carbon emissions globally have been realized through several suggested initiatives. To reduce GHG emissions, auto engine manufacturers generally promote ULSD B20. Renewable ULSD diesel or biodiesel can reduce greenhouse gas emissions by up to 85% without incurring additional costs in new or existing cars. Recent research by the Low Carbon Fuel Standard shows that biodiesel significantly reduces GHG emissions connected to transportation [110].

This innovative case study demonstrates how using biodiesel and renewable fuels has significantly reduced California's transportation-related GHG emissions. California alone used biodiesel and renewable diesel to reduce CO₂ emissions by 4.3 million tons (Mt) under the Low Carbon Fuel Standard program in 2018, surpassing the reductions made by ethanol [110]. Renewable biodiesels have removed almost 18 million tons of CO₂ from the environment.

The CEC claims that locally generated renewable biodiesel supplies lower GHG emissions and the C-footprint while offering consumers cost-effective options. According to the Sustainability for National Biodiesel Board, renewable biofuels may save CO₂ emissions by 20 million metric tons per year without changing how a vehicle is used. That suggests that society will benefit from these circumstances [111].

5. Sustainable Transition

5.1. Role of Biomass Energy

Identifying the function of biomass energy in African and non-African contexts is the first step in achieving sustainability goals. The research question: How can biomass energy contribute to achieving sustainability goals? is addressed in this section. According to the findings, biomass energy is crucial for achieving the global sustainability framework's SDGs 7, 8, 13, and 15. Therefore, in developed and developing nations, its contribution is seen in producing renewable energy, reducing carbon emissions, developing rural-urban areas, and enhancing energy access. The role of biomass energy in advancing sustainability objectives across selected nations is presented in Table 6. The results from certain countries that were selected show the following:

- With large investments in biofuel technology and rural biomass projects, China is leading the world in adopting bioenergy and will play a significant role in achieving the country's carbon neutrality targets by 2060 [112].
- India's biomass contributes to energy equity and lessens dependency on conventional biomass fuels by contributing around 15% of its overall energy consumption, especially in remote areas [113].
- Denmark has achieved almost 30% of its energy from bioenergy sources, making it a global pioneer in integrated biomass heating systems and innovative bioenergy technology [114].

- As a leader in bioenergy innovation, Germany supports the biogas and biofuel industries with strong legislative frameworks, which help the country meet its renewable energy goals under the Energiewende [115].
- Brazil is the world's top bioethanol producer, which helps boost rural economic growth by lowering transportation-related emissions and utilizing sugarcane-based energy systems [116].
- Namibia's “bush to-energy” initiatives, which use biomass from invasive bush species, promote rural livelihoods while addressing environmental and energy concerns [117].
- Ghanaian households continue to rely heavily on biomass energy, with current attempts to enhance traditional biomass use and boost energy efficiency [118].

Table 6. Role of biomass energy in advancing sustainability objectives across selected nations [119]

Country	Biomass Strategies and Programs	Linkages to SDGs	Key Barriers
China	Utilization of crop residues through a national biomass roadmap and rural bioenergy programs	Aligns with SDGs 7, 8, 13: rural electrification, employment creation, and carbon reduction; biomass contributes ~8% (~500 TWh) of the national energy mix.	High technology costs and competition for land resources
India	Agricultural residues harnessed under the National Bioenergy Mission	Supports SDGs 7, 8, 13: expansion of biomass plants, rural employment, reduced coal dependency; biomass share ~12% (~370 TWh)	Weak feedstock logistics and inadequate rural infrastructure
Denmark	Deployment of advanced bioenergy technologies and biomass co-firing in power generation	Addresses SDGs 7, 8, 13: 35% of energy from biomass, creation of green jobs, carbon neutrality goals; biomass ~20% (~43 TWh)	Reliance on imported biomass resources
Germany	Grid integration supported by EEG incentives for biomass energy	Linked to SDGs 7, 8, 13: ~25% share of energy from biomass, employment opportunities, reduction of fossil fuel use; ~9% (~110 TWh)	Land-use pressures and long-term sustainability issues
Brazil	Large-scale sugarcane ethanol initiative	Contributes to SDGs 7, 8, 13: transport bioethanol use, agricultural employment, and GHG mitigation; biomass share ~27% (~160 TWh)	Environmental impacts of monoculture cropping
Namibia	Conversion of encroacher bush via bush-to-biomass projects	Supports SDGs 7, 8, 13, 15: rural electrification, harvesting jobs, and biodiversity protection; estimated potential ~10 TWh	Limited technical know-how and policy shortcomings
Ghana	Traditional use of firewood/charcoal alongside promotion of clean cookstoves	Advances SDGs 7, 8, 13: household energy access, rural employment, carbon savings; biomass share ~40% (~30 TWh)	Inefficient technologies and financial constraints

The research also shows that different levels of success have been made in the biomass energy transition to achieve sustainability objectives. Germany and Denmark are still generating less biomass than they had projected (around 110 TWh and 43 TWh, respectively), utilizing biowaste and biogas as alternative renewable energy sources. With China producing over 500 TWh and India producing about 370 TWh, both countries have achieved great progress. Their primary sources of energy are agricultural waste and residential areas. With a significant biofuel achievement of almost 160 TWh from sugarcane ethanol, Brazil has achieved its biomass share goals.

Namibia and Ghana, on the other hand, rely on conventional biomass sources such as firewood, charcoal, and bush biomass; Ghana meets its goal but needs more sustainable techniques. Due to limited infrastructure, Namibia produces just about 10 TWh, lagging behind the rest of the world.

Emerging and developing nations exhibit differing levels of success and difficulties in reaching their biomass energy targets. In contrast, industrialized economies attempt to reduce their traditional biomass portion to achieve SDGs 7 and 13 (Table 7).

Table 7. Role of biomass energy in the energy mix of selected nations [119]

Country	Total energy from biomass (~TWh)	Planned biomass share (~%)	Current biomass share (~%)	Primary feedstock
India	370	15	12	Crop residues, waste-to-energy
Germany	110	25	9	Biogas, Bioethanol
Namibia	10	12	5	Bush Biomass, Wood Fuel
China	500	10	8	Agricultural residues, forestry waste
Denmark	43	35	20	Wood pellets, biowaste
Brazil	160	27	27	Sugarcane ethanol
Ghana	30	40	40	Charcoal, firewood

Table 8. Extent of SDG attainment in the examined regions [119]

Country	SDG 15 (%)	SDG 7 (%)	SDG 13 (%)	SDG 8 (%)	Average (%)
India	60	80	40	80	65
Germany	60	80	80	80	75
Namibia	80	60	80	60	70
China	60	80	60	60	65
Denmark	80	100	80	80	85
Brazil	60	80	100	80	80
Ghana	60	80	80	80	75

The 2024 United Nations Sustainable Development Goals (UN-SDG) report offers a comprehensive analysis of how biomass energy contributes to the advancement of four key SDGs, Goals 7 and 15, across a diverse set of countries, including China, India, Denmark, Germany, Brazil, Namibia, and Ghana [120]. As shown in Table 8, Denmark leads globally with an impressive 85% contribution score, underscoring its well-developed biomass infrastructure, progressive policy environment, and sustained technological innovation. Brazil follows closely at 80%, particularly excelling in climate-related initiatives through widespread deployment of bioenergy. Germany and Ghana, each with a 75% score, reflect moderate yet consistent progress, indicative

of their continued efforts to integrate biomass solutions amid existing challenges.

Countries achieving scores between 80% and 100% serve as benchmarks, offering critical insights and exemplary practices that can guide others in enhancing their biomass energy strategies. In contrast, those positioned within the 60% to 80% range highlight areas where focused policy reforms, increased financial investment, and technological innovation are essential (Figure 4). This comparative analysis emphasizes the vital role of international cooperation and the exchange of best practices in narrowing performance disparities and accelerating the global transition toward sustainable biomass energy systems.

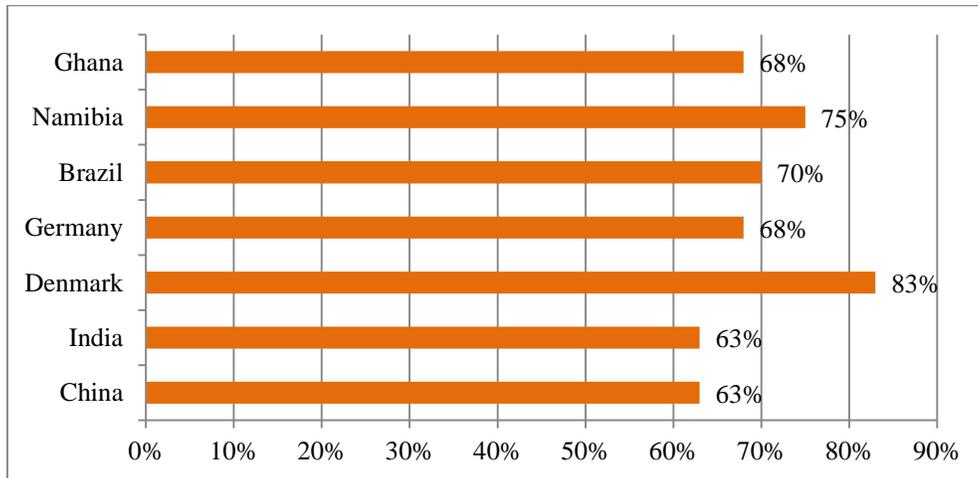


Fig. 4 Overall average progress toward SDG targets across the regions under study [119]

5.2. Conversion Processes

Following an in-depth examination of biomass energy’s role in advancing sustainability, this study turns to a critical inquiry: what technological innovations have emerged to enhance the efficiency and sustainability of biomass energy systems? Across the globe, nations are increasingly embracing

a range of technological solutions aimed at optimizing performance, reducing costs, and minimizing environmental impacts. Table 9 presents a comparative overview of various biomass conversion technologies, evaluating them based on key parameters such as energy efficiency, economic viability, emission levels, and scalability potential.

Table 9. Analysis contrasting different technological approaches for biomass conversion [121]

Technology	Carbon emissions (~kg CO ₂ /GJ)	Efficiency (~%)	Capital cost (~USD/kW)	Energy output (~MJ/kg)	LCOE or scalability (~USD/kWh)
Fermentation	20-30	50-70	2000-5000	20-25	0.06-0.12
Gasification	30-50	70-85	4000-7000	30-45	0.07-0.14
Combustion	90-110	15-40	1500-3000	18-Oct	0.04-0.08
Pyrolysis	50-70	40-75	3000-6000	25-35	0.08-0.15

A comprehensive interpretive review reveals that gasification has emerged as one of the most efficient biomass conversion technologies, offering energy efficiencies between 70% and 85%. While it demands higher capital investment, its advantages, such as low emissions and the generation of high-quality syngas, have led to its accelerated adoption in countries like Germany and Denmark [119, 122]. In parallel, anaerobic digestion (or fermentation) has gained considerable traction in nations such as China, India, and Brazil, where it plays a pivotal role in the production of bioethanol and biogas.

remains essential for strengthening energy security and fulfilling global sustainability objectives. In developed nations like Denmark and Germany, significant strides have been made in implementing integrated biomass systems, with an emphasis on cleaner, high-efficiency biofuel technologies. In contrast, rapidly developing economies such as China, India, and Brazil have concentrated efforts on bioethanol and biogas production, leveraging their abundant agricultural residues and organic waste streams. Across Africa, countries like Namibia and Ghana are still in the nascent stages of technological deployment, focusing on cost-effective, scalable solutions such as small-scale gasification units and hybrid bioenergy platforms. Despite these efforts, persistent challenges that include constrained financial resources, gaps in technical capacity, and fragmented or inconsistent policy environments continue to impede the widespread adoption and optimization of biomass energy technologies.

As presented in Table 10, technological progress in biomass energy conversion varies considerably among countries, influenced by factors such as resource endowment, policy frameworks, and the maturity of technological infrastructure. Advancing biomass conversion technologies

Table 10. Progress in biomass energy conversion technologies in selected nations [119]

Country	Key Advancements	Technological Focus	Application Area
India	Small-scale biogas technologies	Biogas systems	Agriculture and domestic energy
Germany	Advanced bioethanol production	Second-generation biofuel	Transport and industrial sector
Namibia	Gasification and bioenergy mix	Hybrid biomass technologies	Rural electrification
China	Biogas plants	Anaerobic digestion	Rural electrification
Denmark	High-efficiency biomass plants	Combined heat and power	Industrial and urban heating
Brazil	Large-scale sugarcane ethanol	Ethanol production	Transport sector
Ghana	Off-grid biomass electricity	Biomass gasification	Remote communities

5.3. Sustainability Mandates

This section explores comparative pathways for advancing global sustainability objectives, focusing on the concluding research question: what policy implications arise from the promotion of biomass energy within the context of sustainable development? It is widely acknowledged that effective policy frameworks play a pivotal role in accelerating the adoption of biomass energy by offering regulatory stability, financial incentives, and strategic guidance to stakeholders across the value chain. The findings indicate

notable disparities in policy design and implementation among countries, shaped by differing economic priorities, institutional capacities, and the availability of natural and technological resources [119].

Table 11 highlights the strong policy frameworks in developed countries like Germany and Denmark, where measures such as feed-in tariffs, subsidies, carbon pricing, and Renewable Portfolio Standards (RPSs) have been adopted to advance biomass energy.

Table 11. Regulatory frameworks enabling the expansion of biomass energy [123]

Country	Incentives and Support Mechanisms	Policy Framework	Regulatory Measures
India	Subsidy programs	National bioenergy mission	Regulatory policies
Germany	Renewable energy subsidies	Feed-in tariffs	Regulatory compliance
Namibia	Donor-driven programs	Pilot biomass projects	Limited regulations
China	Financial subsidies	National renewable energy targets	Mandatory grid connections
Denmark	Feed-in tariffs	Renewable portfolio standards	Carbon pricing
Brazil	Agricultural residue utilization	Bioenergy integration programs	Financial incentives
Ghana	Subsidy programs	Regional energy strategies	Policy monitoring

In Brazil, bioenergy policy has centered on incorporating agricultural residues into national energy systems, bolstered by government-backed financial incentives to encourage widespread adoption. However, their impact has been undermined by bureaucratic inefficiencies and inconsistent policy enforcement.

Meanwhile, in developing African nations such as Namibia and Ghana, biomass policy remains nascent, primarily limited to pilot initiatives, regional development strategies, and donor-supported programs. These efforts often struggle with weak enforcement, limited financing, and the absence of comprehensive monitoring systems, thereby constraining their scalability and long-term viability.

Figure 5 illustrates the relative effectiveness of biomass energy policy frameworks across the selected countries, reflecting a synthesis of policy strength, implementation quality, and observed outcomes. While developed nations demonstrate notable success in advancing biomass energy adoption, their experiences offer valuable lessons for emerging and developing economies seeking to align with global sustainability objectives. To this end, several strategic recommendations emerge: (1) introducing targeted incentives to stimulate investment in biomass energy, (2) fostering collaborative public-private partnerships to drive innovation and scalability, and (3) enacting comprehensive regulatory reforms to create a more enabling policy environment. These measures are critical to unlocking the full potential of biomass as a sustainable and nature-aligned energy solution.

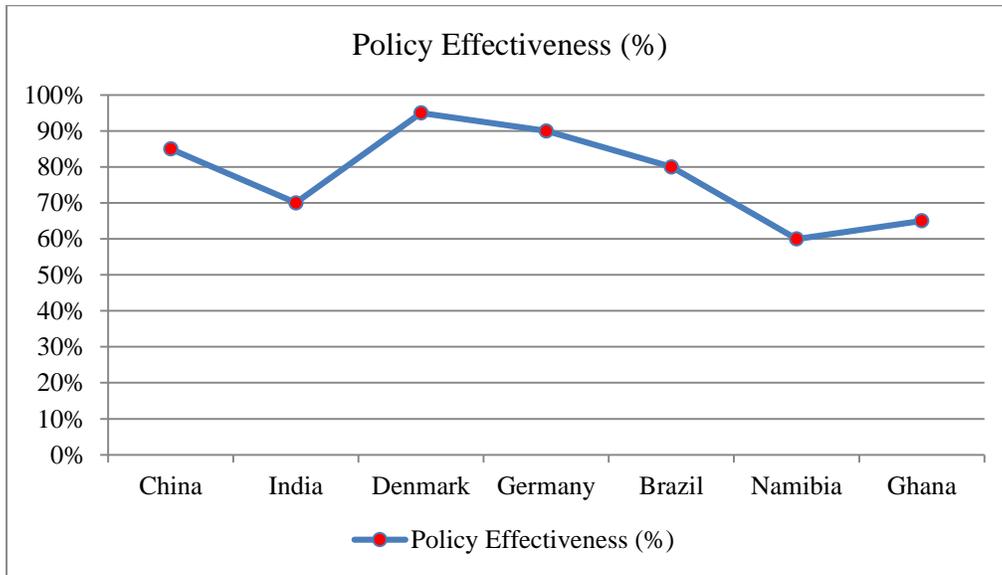


Fig. 5 Assessment of the effectiveness of policy mechanisms promoting biomass energy adoption [124]

The findings indicate notable disparities in policy effectiveness across countries in promoting biomass energy adoption. China demonstrates a strong performance with an effectiveness rating of 85%, underpinned by substantial capital investment, strategic policy orientation, and the integration of biomass energy within broader national energy agendas. India follows with a 70% effectiveness score, reflecting the impact of regionally implemented programs and

financial incentive schemes, even though within a moderately coordinated framework. Denmark leads globally with a remarkable 95% effectiveness, driven by robust institutional governance, transparent regulatory systems, and innovative financing models that have collectively propelled its biomass sector. Germany also scores highly at 90%, driven by ambitious renewable energy mandates and sustained political will to advance environmentally responsible energy strategies.

Ghana, with a 65% rating, shows moderate policy impact, primarily through localized bioenergy projects and supportive financial instruments. These divergent outcomes underscore the necessity of context-specific policy design—tailored to each country’s socio-economic realities and environmental conditions to fully harness the potential of biomass energy in advancing sustainable development.

5.4. Current Challenges and Prospects / Prediction of Biofuel Production

The continued reliance on fossil fuel-based energy systems presents serious environmental, climatic, and socio-economic challenges, casting doubt on their long-term sustainability. At present, fossil fuels account for over 80% of the global energy supply. Projections from the International Energy Report suggest that worldwide energy demand will rise by 28% by 2040 [125]. In India alone, energy consumption is expected to grow by 25%, nearly doubling within the next two decades.

Against this backdrop, the global spotlight has increasingly turned toward biofuel production from biomass as a viable, environmentally responsible alternative that aligns with the objectives of the SDS. Numerous innovative and cost-effective technologies, along with a growing portfolio of renewable biofuel feedstocks, offer promising pathways for enhancing domestic energy self-reliance and promoting long-term sustainability. Nevertheless, the biofuel sector continues to face a set of persistent and critical challenges, which are outlined as follows:

- The conversion of biomass into biofuels requires the development of efficient and environmentally sustainable pre-treatment strategies that facilitate enzymatic access to cellulose, reduce lignin content, and increase the availability of fermentable sugars, crucial steps for enhancing downstream fermentation processes [126]. However, many of the pre-treatment techniques currently in use present notable drawbacks. Chief among these is the generation of inhibitory by-products. These compounds can suppress microbial activity, particularly yeast, leading to extended lag phases, reduced cell growth rates, and ultimately, lower yields of ethanol and hydrogen [127]. Despite these challenges, integrating biorefinery principles offers a promising pathway to mitigate such limitations and improve the overall efficiency and viability of the biomass-to-biofuel conversion process.
- The transformation of oils, fats, or lipids into biodiesel necessitates an efficient transesterification process to ensure the production of high-quality fuel. Enhancing biodiesel properties by optimizing fatty acid composition can address performance challenges often associated with biodiesel–diesel blends in compression ignition engines. To achieve this, a comprehensive evaluation of both fuel and oil characteristics is essential. Key parameters include the FAME profile, acid value, residual methanol

content, oxidative stability, and properties influencing fuel delivery and filtration, such as cold flow behavior and filter plugging tendency.

- Bio-oil produced through fast pyrolysis of biomass presents a promising route for heat and power generation; however, its application is often constrained by high costs, largely attributed to its relatively low energy density. Addressing these limitations requires precise modeling of heat and mass transfer processes, which are critical for improving system efficiency, minimizing energy consumption, and reducing reaction time. One of the key challenges lies in selecting an appropriate and robust thermochemical conversion pathway. Nevertheless, the performance of such systems can be substantially enhanced by increasing the energy content of the pyrolysis products and facilitating downstream upgrading and refining of the bio-oil into higher-value fuels [128].
- Food versus fuel: Addressing the long-standing food-versus-fuel debate requires increased public and stakeholder awareness of the advancements and benefits of biofuel technologies. Promoting the use of non-edible inputs, such as oil-rich food waste and other readily available feedstocks not competing with food supply chains, can play a pivotal role in lowering production costs and easing tensions surrounding land and resource allocation between food and energy sectors. Enhanced understanding and strategic feedstock selection are thus essential in mitigating this critical sustainability concern.
- Biofuels as transportation fuel alternatives offer a compelling pathway for addressing climate change, while simultaneously creating avenues for diversifying the global energy mix and enhancing the long-term resilience and security of energy supply chains [129].
- Promoting cogeneration biofuel technologies tailored to meet localized community energy demands presents a promising solution to the growing global challenge of waste management, particularly in countries like India. These integrated systems not only offer a sustainable pathway for waste valorization but also contribute to decentralized energy generation. However, the broader adoption of biofuels continues to spark debate due to a range of social, economic, and environmental concerns. Key among these are the potential disruptions to agricultural markets and the greenhouse gas emissions associated with indirect land-use change. To fully assess the viability and long-term sustainability of biofuels, a comprehensive and multidimensional evaluation of their impacts is essential [130].
- Although numerous studies have explored the technological advancements, economic viability, and social dimensions of biofuel production, significant limitations remain regarding economic and technical feasibility. One notable example is the conversion of microalgae into biofuels, which, despite its promise, largely remains at the research or pilot scale. This

emerging technology warrants greater global attention, given its potential to substantially lower lifecycle Greenhouse Gas (GHG) emissions when compared to conventional fossil fuels [131].

The technical and socio-economic barriers to scaling biofuel production are presented in Figure 6.

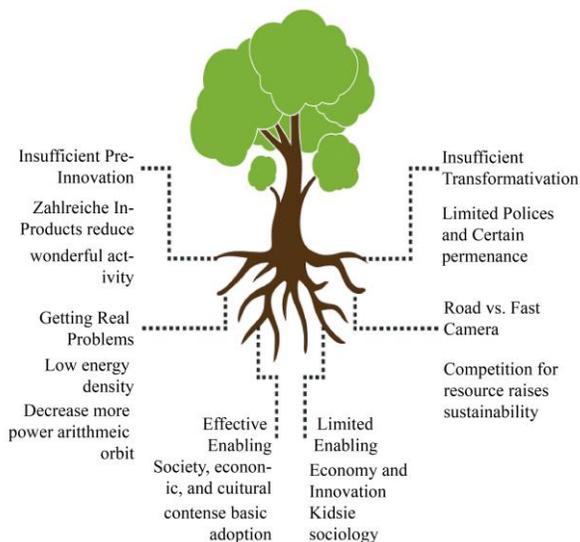


Fig. 6 The technical and socio-economic barriers to scaling biofuel production

5.5. Emerging Technologies, Global Policy Trends, and Socio-Economic Impacts

Beyond conventional processes, several emerging technologies are redefining the landscape of FVW valorization. Recent advances in deep eutectic solvents and ionic liquids have shown promise in disrupting lignocellulosic structures for efficient ethanol yields above 90% [132]. In biodiesel pathways, nano-catalysts and enzyme immobilization techniques are reducing transesterification time while enhancing catalyst reusability [133]. Similarly, biohydrogen production is benefiting from microbial electrolysis cells and hybrid dark-photo fermentation systems, which significantly increase H₂ recovery rates compared to conventional fermentation [33]. These innovations indicate a paradigm shift toward integrated biorefinery systems, wherein FVW is valorized not only for biofuels but also for high-value co-products such as organic acids, bioplastics, and platform chemicals.

Parallel to technological advances, global policy trends strongly influence the pace of FVW-to-bioenergy adoption. The European Union’s Fit-for-55 package sets binding targets for renewable fuels in transport, while the U.S. Renewable Fuel Standard mandates increased blending of advanced biofuels. Brazil’s Renova Bio policy and India’s updated National Bioenergy Mission (2023) demonstrate how developing nations are prioritizing agricultural and food waste

streams to meet energy security and sustainability goals. These frameworks highlight the role of policy certainty and financial incentives in overcoming investment barriers [134-136].

The socio-economic implications of FVW valorization are equally noteworthy. In Brazil, the sugarcane ethanol industry has generated hundreds of thousands of rural jobs and revitalized agricultural economies. In India, pilot projects converting mango and banana waste into ethanol have enhanced farmer income diversification while reducing open dumping practices [137]. In Sub-Saharan Africa, small-scale waste-to-energy plants improve household energy access, reduce reliance on traditional biomass, and cut indoor air pollution, thereby reducing healthcare costs [138]. In Europe, adoption of biofuel blends has been directly linked to improved urban air quality, generating significant public health savings [139, 140].

These insights illustrate that the transition toward FVW-derived bioenergy is not merely a technological endeavor but also a socio-economic and policy-driven process. Integrating emerging technologies with robust policy frameworks and case-based socio-economic benefits will be critical for scaling FVW bioenergy systems globally. The policy, economic, social, technological, environmental, and legal enablers of biofuel development are presented in Figure 7.

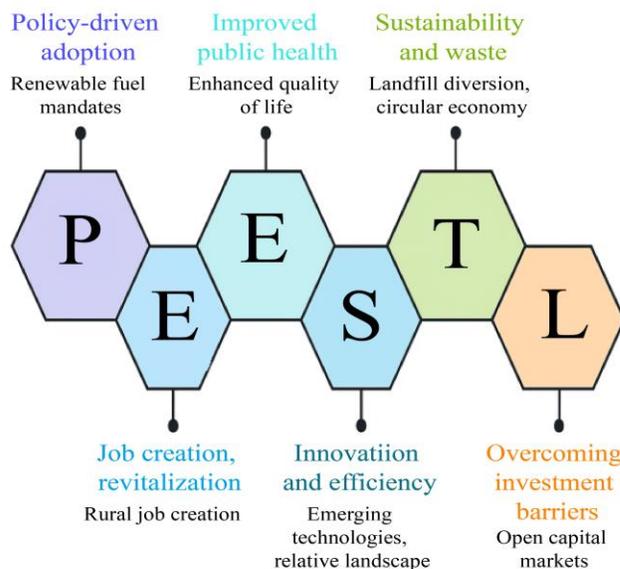


Fig. 7 The policy, economic, social, technological, environmental, and legal enablers of biofuel development

6. Conclusion

This review synthesized the current state of FVW valorization for bioenergy production, covering biogas, bioethanol, biodiesel, and biohydrogen pathways. While the analysis confirms the significant role of FVW in advancing renewable energy and circular bioeconomy practices, the

findings also underscore that the environmental and economic benefits are conditional, context-specific, and limited by technical and policy challenges. A balanced perspective, therefore, is essential to guide realistic implementation and research priorities. The key outcomes of this study are as follows:

- Bioethanol from lignocellulosic FVW can achieve glucose conversion yields exceeding 90% under optimized pretreatment, though inconsistent feedstock composition and lack of standardized protocols remain major barriers.
- Biodiesel production via transesterification of FVW-derived oils demonstrates high conversion efficiencies (up to 93%), but its viability is constrained by low lipid content and high processing costs.
- Biogas generation through anaerobic digestion benefits from co-digestion strategies, which can enhance methane content up to 68%, yet challenges persist with rapid acidification and inhibitory by-products.
- Biohydrogen offers the highest GHG mitigation potential, with yields reaching 63 mL/g VS under optimized conditions, but scalability is hindered by low overall energy recovery and microbial sensitivity.
- Environmental benefits, including GHG reduction and pollutant mitigation, are evident but vary depending on feedstock availability, conversion efficiency, and system boundaries of lifecycle assessments.
- Scaling challenges span technical (pretreatment bottlenecks, microbial robustness), economic (high costs, market competition), and policy dimensions (weak regulatory frameworks, insufficient incentives).

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Future research should prioritize the development of cost-effective, environmentally benign pretreatment methods and advanced catalytic systems such as nanocatalysts and immobilized enzymes. Microbial engineering for robust and high-yield hydrogen production, coupled with integrated biorefinery approaches that co-produce fuels and value-added chemicals, will be essential to improve techno-economic feasibility. Expanding lifecycle-based meta-analyses and techno-economic assessments will provide clearer benchmarks for FVW bioenergy relative to competing renewable technologies. Moreover, supportive policy frameworks and case-driven socio-economic studies are critical to enhance scalability, foster rural employment, and integrate waste-to-energy solutions into sustainable national energy strategies. In conclusion, Fruit and Vegetable Waste represents a credible yet underutilized feedstock for bioenergy production. Its successful transition from laboratory and pilot studies to commercial scale will depend on a realistic alignment of technological innovation, cost efficiency, and enabling policy support. By acknowledging limitations while strategically pursuing innovation and governance reform, FVW-derived bioenergy can evolve into a pivotal contributor to carbon neutrality, energy equity, and Sustainable Development Goals.

Acknowledgments

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