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Synergistic Valorisation of Fruit and Vegetable Waste for Bioenergy Production: A Review

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Abstract: This review provides comprehensive information on the synergistic valorization of fruit and vegetable waste (FVW) for bioenergy production, addressing the urgent need for sustainable waste management and renewable energy sources. Due to their high organic content and substantial methane formation potential, FVW presents significant challenges. This review examines anaerobic digestion, composting, and thermochemical conversion processes, including pyrolysis and gasification. The emphasis is given to the combined use of these pathways, which allows maximizing the energy recovery and the resource utilization factor as well as reducing the environmental burden. The critical analysis of the main factors influencing the effectiveness of these processes is provided waste composition, process adjustments, and technical advancements. Recent studies indicated that pre-treatment methods improved conversion efficiency by up to 30%, and integrating multiple conversion pathways enhanced energy recovery by 20-40%. This comprehensive review concludes by discussing the prospects and challenges of commercial bioenergy production from FVW, integrating findings from recent scientific investigations and technological breakthroughs. The results of this work aim to enhance sustainable waste management strategies and contribute to a holistic circular bioeconomy vision.

Keywords: Food and Vegetable Waste, Sustainable environment, Bioenergy, Commercial Bioenergy Production.

1. Introduction

In this regard, with the constant growth of global energy demand and the urgent issue of finding sustainable solutions for waste management, it becomes imperative to search for commercially feasible alternatives of renewable energy production. One of the most promising types of biomass for this goal is fruit and vegetable waste, which is characterized by abundant availability and high organic content [1]. However, inefficient means of this organic residue action led to environmental concerns and waste of available resources, as well as missed potential for energy production. This type of waste accumulates within the agricultural and food processing industries in the form of various residues, such as peels, seeds, pulp, and trimmings. Although the use of residual biomass to produce bioenergy is possible, a substantial part of the waste is disposed of in landfills, contributing to pollution. The need to integrate fruit and vegetable waste in bioenergy production pathways is spurred by the interest in value creation along with environmental protection effects [2]. The objective of the research is to elaborate on various approaches to fruit and vegetable waste valorisation within bioenergy production processes, focusing on the interaction of several valorisation pathways to enable a synergistic effect. A combination of several conversion processes is considered to allow greater energy production and resource effectiveness. The first bioenergy production method is anaerobic digestion, which involves the degradation of organic substances without oxygen and allows the production of biogas as well as digest. Given that fruit and vegetable waste are characterized by a substantial amount of moisture and good biodegradability, they are a suitable feedstock for anaerobic digestion [3]. Moreover, the remaining organic substance after anaerobic digestion can be treated through composting, an aerobic process in which organic matter is decomposed and the resulting compound is used as a soil amendment. Additionally, fruit and vegetable waste can be used for bioenergy via thermochemical conversion, describing a process by which biomass is turned into energy through heating without oxygen. The types considered in the study are pyrolysis, a process during which biochar, bio-oil, and syngas are produced for further use, and gasification, which allows for the creation of syngas due to partial oxidation.

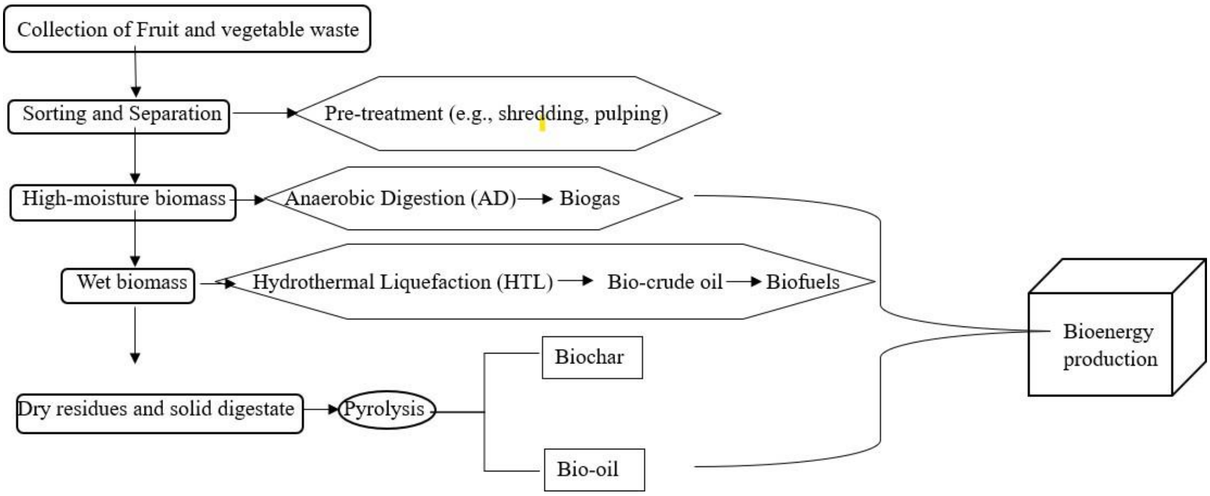

Figure 1. Fruit and Vegetable Waste for Bioenergy Production

All of the above methods abide by the principle of cascading, ensuring that the waste generated from one process is used for the next process, resulting in minimal waste and maximal resource recovery. This way, the processing efficiency and economic feasibility of the process increase [4]. The research thus provides a critical analysis of existing knowledge, current challenges, and prospects for the integration of fruit and vegetable waste in bioenergy projects. The assessment allows for deriving valuable perceptions for policymakers, scientists, and industry representatives working to promote sustainable waste processing and a circular bioeconomy. Figure 1 illustrates the valorisation of Fruit and Vegetable Waste (FVW) for Bioenergy Production. This research uniquely explores the synergistic integration of several bioenergy production methods to enhance the valorization of fruit and vegetable waste. The valorisation of fruit and vegetable waste (FVW) for bioenergy production addresses waste management issues and energy demands by integrating Anaerobic Digestion (AD), Hydrothermal Liquefaction (HTL), and Pyrolysis [5-8]. AD effectively converts high-moisture organic waste into biogas and digestate, which can be used as a soil conditioner. HTL processes wet biomass into bio-crude oil, suitable for conversion into biofuels. Pyrolysis thermally decomposes dry biomass into biochar, bio-oil, and syngas, enhancing soil fertility and providing alternative energy sources. The integrated approach maximizes resource recovery and energy production by utilizing the strengths of each technology, fostering a circular economy model in waste management. This study aims to minimize waste and maximize resource recovery, providing a comprehensive analysis of current challenges and future prospects for sustainable waste processing and circular bioeconomy.

2. Properties and Characterization of Fruit and Vegetable Waste

Fruit and vegetable waste discards a wide range of organic residues throughout the agricultural and food processing sectors [9]. The composition of Fruit and Vegetable Waste (FVW) must be characterized to identify its variability and potential for bioenergy generation. The moisture content, organic content, nutrient composition, lignocellulosic content, and, biochemical composition are other major parameters for FVW characterization. The moisture content is a major parameter that can help in determining the suitability of FVW for specific bioenergy conversion processes. Anaerobic digestion can be carried out on wet FVW; various preprocessing measures are required before thermochemical conversion methods like pyrolysis and gasification can treat organic matter with a high percentage of water. The quantity of organics, measured as volatile solids, is an optimal measure of the energy content of FVW and its suitability to produce biogas through anaerobic digestion. Nutrient composition includes the amounts of trace elements present in FVW which influence the fertility value of the FVW-derived digestate and compost. In addition, the nutrient composition, expressed herein as nitrogen, phosphorus, and potassium, also has a significant implication on the final product quality, fertilization value, and the application to the agricultural sector. The lignocellulosic material in FVW, which consists of cellulose, hemicellulose, and lignin, also determines the suitability for thermochemical conversion processes into biofuels such as bio-oil, biochar, and gas [10]. High moisture content is suitable for anaerobic digestion, while pyrolysis and gasification necessitate pretreatment such as drying. More significant lignocellulosic carbon yields and heating values are provided to FVW-derived biochar and syngas. However, the toughness of the material, particularly lignin, may be a barrier to effective biomass pretreatment and transformation processes. Biochar materializes through the pyrolysis of FVW, while biochars and bio-oils are produced. These measures are enabled by the material's biochemical composition, including sugar, starch, lipid, and protein levels. FVW characterization methods also include proximate and ultimate analysis, and elemental analysis; spectroscopic methods, such as FTIR and NMR; and chromatography such as Gas Chromatography and Liquid Chromatography; and thermoanalytical techniques Thermogravimetric Analysis [11]. These methods provide insight into the physicochemical characteristics, molecular arrangement, and thermal behaviour of FVW, allowing for process design and feedstock selection for effective bioenergy generation. The characterization of FVW composition is crucial to identify the appropriate conversion methods and optimization techniques for the process, resulting in maximum resource recovery while minimizing environmental harm. Table 1 describes about the various characterizations along with the importance.

One of the most critical hurdles in EEG signal analysis is the presence of noise and artifacts, such as eye blinks and muscle movements, which significantly affect the quality of data. Methods such as Independent Component Analysis (ICA) and Principal Component Analysis (PCA) have been widely used to mitigate these artifacts, with considerable success [4]. Additionally, advances in machine learning and signal processing have led to the development of novel feature extraction techniques, improving the accuracy and reliability of EEG-based diagnosis [5]. The high dimensionality and redundancy of EEG data often lead to computational inefficiencies and can result in model overfitting. Strategies like feature selection and dimensionality reduction, combined with cross-validation techniques, have been employed to overcome these issues [6]. Furthermore, advancements in deep learning architectures, such as convolutional neural networks (CNNs) and long short-term memory (LSTM) networks, have shown promise in capturing complex temporal dependencies within EEG data [7]. Despite the significant progress in EEG-based neurological diagnosis, challenges remain, including the inter- and intra-subject variability in EEG signals and the limited availability of comprehensive datasets. Addresses the variability issue by introducing robust feature extraction techniques that improve the generalization capabilities of EEG-based diagnostic models [8]. Nonetheless, the use of EEG as a diagnostic tool for neurological disorders continues to grow, offering great potential for early detection and intervention.

2.1 Types and sources of fruit and vegetable waste

Fruit and vegetable waste is broad and diverse and may occur all along the growing production chain, from farming to processing and consumption. Sources of FVW include agricultural production that generates residues from harvesting, sorting, and grading, such as peels, leaves, stems, and other trimmings. Postharvest processing activities generate even more significant volumes of FVW from peeling, shredding, cutting, and packaging that include other by-products like pomace, pulp, seeds, and rinds. Retailing also finds its way in this problem since the unsold or expired produce as well as merchandised trimmings and damaged fruits can also be wastes or a product for reuse. In the consumer sector, household, restaurant, and institutional food spoilage and preparation account for the primary generation of FVW containing discarded peels, seeds, and spoil [12]. Also, a share of post-consumer waste thrown away into the municipal solid waste stream is classified as FVW. Therefore, to implement effective valorization strategies that target waste reduction, resource recovery, and bioenergy production, it is important to recognize the many types and sources of FVW. Such practices are critical for effective waste management and the development of a circular bioeconomy, as organic residues are transformed into valuable resources, reducing the ecological costs associated with waste disposal.

This table 2 highlights the broad and diverse nature of FVW and its occurrence along the growing production chain from farming to processing and consumption. Recognizing these various types and sources of FVW is crucial for developing effective valorization strategies, waste management practices, and promoting a circular bioeconomy by transforming organic residues into valuable resources.

Table 1. Characterization of Fruit and Vegetable Waste

Characteristic	Description	Importance	References
Organic Content	Percentage of organic matter in FVW	Determines bioenergy potential	[13]
Moisture Content	Percentage of water content in FVW	Influences digestion efficiency	[14]
Nutrient Composition	Levels of nitrogen, phosphorus, and potassium	Affects microbial activity and biogas yield	[15]

Table 2. Classification and Sources of Fruit and Vegetable Waste (FVW)

Category	Sources	Illustrations	References
Agricultural Production	Residues from harvesting, sorting, and grading	Peels, leaves, stems, trimmings	[16]
Postharvest Processing	Activities such as peeling, shredding, cutting, and packaging	Pomace, pulp, seeds, rinds	[17]
Retailing	Unsold or expired produce, merchandised trimmings, damaged fruits	Spoiled produce, trimmings	[18]
Consumer Sector	Household, restaurant, and institutional food spoilage and preparation	Discarded peels, seeds, spoil	[19]
Municipal Solid Waste	Post-consumer waste	General FVW from household and commercial waste streams	[20]

2.2 Composition analysis: organic content, moisture, carbohydrates, lipids, proteins, and lignocellulose content

Composition analysis of FVW is crucial to determine its potential for bioenergy production and valorization. Organic content, usually in the form of volatile solids, provides an insight into the energy potential of FVW to ascertain its biochemical conversion potential. High organic content implies a potential for biogas production through anaerobic digestion, which is significantly determined by the availability of organic substrates essential for microbial metabolism. Moisture content, another important parameter, influences the suitability of FVW for bioenergy conversion pathways he majors biochemical components included in FVW are carbohydrates, lipids, proteins, organic and lignocellulosic contents, and the following is their possible implications of the subsistence of FVW to bioenergy and biofuel valuation [21]. Fermentable carbohydrates include sugars and starch which are converted into bioethanol through enzymatic hydrolysis and fermentation. Lipids which comprise oil seeds and oily fruit are convertible to bio-oil through transesterification. The protein content, which is highly entailed in legumes fruits and vegetables is hydrolysable to amino acids which are further hydrolysable to biogas or as N source in biochemical processes. The lignocellulosic content in fruit and vegetable, comprising of cellulose, hemicellulose, and lignin also influences the subsistence of FVW to thermochemical conversion to biofuels and biochemical [22]. Cellulose and hemicellulose are converted into bioethanol while lignin enhances the calorific value and thermochemical stability of biochar and pyrolysis during thermochemical conversion. Therefore, analysis of fruit metabolic composition is important in making an informed decision in identifying a suitable valorization pathway and optimizing the process parameters for bioenergy production.

2.3 Factors influencing the composition of fruit and vegetable waste

A wide range of factors from agriculture and post-harvest to processing and consumption affects FVW composition. The most significant source of variability in FVW composition is closely linked to harvest crops type, cultivar, ripeness stage, harvesting method, and storage. Due to the different biochemical profiles of fruits and vegetables, the distribution of organic constituents and nutrients found in their waste stream is affected. For instance, fruits with high sugar contents, such as grapes and bananas, would result in FVW with a high percentage of carbohydrates, while oil-rich seeds from avocado and olive processing would result in high lipid contents. Additionally, after-harvest sorting, washing, peeling, and trimming also have the potential to impact the composition of FVW offering different edible and inedible fractions [23, 24]. Food industries produce several by-products and residues depending on their processing technique, including juicing, canning, and freezing. For example, fruit juice extraction increases sugars and fibers in pomace and vegetable canning yields a liquid waste stream with high salt contents and organic acids. FVW composition is also directed by downstream consumer behavior and preferences such as overconsumption, poor storage, aesthetic standards, and dietary choice. Seasonal consumption and fruit and vegetable availability also affects the composition and amounts of waste generated all year. These factors interact and may influence the development of efficient FVW pre-treatment strategies to optimize bioenergy production. Attaining resource recovery, conservation yield and net energy efficiencies, and environmental friendliness through circular economy principles necessitate multi-impact valorization.

3. Bioenergy Production Technologies

Biofuels are classified into four generations based on their feedstock and production technologies. First-generation biofuels are produced directly from food crops like corn, sugarcane, and vegetable oil, with common examples including bioethanol and biodiesel. Second-generation biofuels are derived from non-food biomass such as agricultural residues, wood chips, and waste materials, addressing the food versus fuel debate. Third-generation biofuels are produced from algae and other microorganisms, which have high lipid content and faster growth rates compared to traditional crops. Fourth-generation biofuels focus on genetically engineered crops and microorganisms to produce biofuels with higher yields and lower environmental impacts, including those that capture and store carbon dioxide [25]. Various bioenergy production technologies exist with potential conversion routes from FVW towards high-yield energy carriers that would help manage the mentioned organic residue sustainably and diversify renewable energy portfolio. Pretreatment technologies are essential for the efficient conversion of biomass into biofuels. These include physical pretreatment methods such as milling, grinding, and extrusion to reduce particle size and increase surface area for enzymatic action. Chemical pretreatment involves the use of acids, alkalis, or solvents to break down lignocellulosic biomass and release fermentable sugars. Physico-chemical pretreatment combines physical and chemical methods, such as steam explosion and ammonia fiber expansion (AFEX), to enhance biomass digestibility. Biological pretreatment utilizes microorganisms or enzymes to degrade lignin and hemicellulose, making cellulose more accessible for hydrolysis [26]. Among fermentation-based technologies used to convert the FVW organic matter is the well-known anaerobic digestion process, which produces a mixture of methane and carbon dioxide, known as biogas.

Figure 2. Technological Improvement in Bioenergy Production

It uses microbial activity to degrade complex organic compounds in the absence of oxygen, which then results in biogas as a renewable output energy. Apart from gas emission reductions during the FVW fermentation process, some developing technologies also use the fully digested waste, also known as digestate, as a soil amendment Fermentation is a crucial biochemical conversion method for producing biofuels from fruit and vegetable waste (FVW). This process involves the use of microorganisms to convert sugars into bioenergy products such as bioethanol and biobutanol. Bioethanol, produced through the fermentation of sugars by yeast, can be blended with gasoline or used as a standalone fuel due to its high octane rating and compatibility with existing infrastructure. Biobutanol, another fermentation product produced by Clostridium species, has a higher energy content than bioethanol and can be used in gasoline engines without modifications [27].

The alternative way to valorize the FVW is to use the three thermochemical conversion technologies pyrolysis and gasification. Pyrolysis is a thermochemical decomposition without an air environment, which then produces biochar, bio-oil, and syngas. Biochar acts as a soil conditioner and carbon sink; bio-oil and syngas are used for heat and power generation. Gasification is a high-temperature thermal biomass breakdown using partial oxidation to create a flammable gas mixture, syngas. It allows the flexibility of its downstream use, such as combined heat and power and the synthesis of fuels or chemicals. Furthermore, biochemical conversion methods such as fermentation and enzymatic hydrolysis break the fermentable sugars and carbohydrates present in the FVW into bioenergy. The two methods involved the use of microorganisms and enzymes to convert sugar into bioethanol, which could be blended with gasoline or utilized as a single fuel source [28]. Thus, the synergistic combination of multiple bioenergy production technologies would allow for the maximization of energy recovery from sugar-containing FVW. Synergistic valorization would be optimizing the combination of different conversion pathways, enabling the FVW feedstock to be fully utilized, and minimizing the waste, supporting the circular bioeconomy. Figure 2 illustrates the Major Bioenergy Production Technologies.

3.1 Anaerobic digestion: principles, process parameters, and biogas yield

Anaerobic Digestion (AD) is the most effective single method for valorizing fruit and vegetable waste. It efficiently processes high-moisture, biodegradable materials to produce biogas, a renewable energy source, and digestate, a nutrient-rich soil conditioner. This method not only addresses waste management but also supports sustainable energy production and reduces greenhouse gas emissions, making it a highly beneficial and environmentally friendly. It is the process through which the organic material in the FVW is converted into biogas in the absence of oxygen by the action of microorganisms. In addition to that, the process is aided by a group of microorganisms acting concurrently to decompose the complex organic materials in FVW. At the core of AD are four stages, namely hydrolysis, acidogenesis, acetogenesis and methanogenesis. Monomers rendered in this process through the action of acidogenesis through the fermentation of monomers to acids and other solubilized organic materials [29]. Acidogenesis is followed by acetogenesis, where some of the acids are converted to acetic acid, hydrogen and carbon dioxide play. Finally, the last process stage is the methanogenesis, which is the microbial degradation of acetic acid or hydrogen – and carbon dioxide to produce methane and carbon dioxide. A combination of process-based parameters influences effectiveness and flexibility of AD while processing FVW. They include temperature, pH, OLR, Hydraulic retention time, substrate to inoculum ration. Standard operating parameters are usually set at mesophilic or thermophilic temperatures and neutral pH levels with controlled OLR and HRT to ensure microbial activity and stability. In addition to these conditions, suitable carbon-to-nitrogen ratios in the feedstocks ensure optimum microbial growth and biogas formation. The volume of biogas obtained during AD of FVW depends on the composition of the feedstock used, as well as numerous other factors including process conditions and the configuration of the reactor. Generally, high-yielding fruits with large quantities of digestible organics such as fruit pulps and vegetable trimmings tend to produce higher biogas yield. However, factors leading to substrate accessibility and distribution affect the biogas formation process. Moreover, other parameters influence the design and manipulations of the reactor to maximize the biogas formation rate and the content of methane. Therefore, understanding the above principles and operational parameters is necessary for optimizing biogas yield and energy recovery from FVW through AD. Finally, the application of anaerobic digestion technology may facilitate a synergistic approach that combines AD with other bioenergy conversion technologies to enhance sustainable waste management practices while generating renewable energy.

3.2 Thermal conversion processes: pyrolysis, gasification, and combustion

Pyrolysis, gasification, and combustion are some of the most flexible uses of thermal conversion technology for the procurement of bioenergy commodities from FVW. Pyrolysis is defined as the decay of biomass using heat in the absence of air to create biochar, bio-oil, or syngas. In brief, FVW is exposed to rapid thermal shrinkage, resulting in the breakdown of organic species into gaseous and liquid materials and leaving char. Biochar is a solid, carbon-rich material that can be added to the soil to improve soil health and restore carbon levels. Bio-oil, which is a stable, varied form of liquid fuel for use in heating, electric traction, and biochemical technology, is made up of bio-oil [30]. Syngas, which is made up of carbon oxide, hydrogen, and tiny volumes of methane, can be burnt in a gas turbine or engine for electricity or turned to create liquid fuels and specialty materials. Syngas is made up of carbon monoxide, hydrogen and small quantities of methane and can be burned in gas turbines or engines for electric power or converted to liquid fuels and chemicals [31]. Gasification is another thermochemical process that converts FVW into a burnable gas mix called syngas through partial oxidation at high temperature. A controlled amount of oxygen or steam is added to the reactor in gasification, enhancing the extent of gas product formation by introducing the waste feed. Syngas from FVW gasification can be used to fuel combined heat and power systems, industrial processes, and artificial fuel creation. Combustion is the most typical thermal conversion technology, in which FVW is burned to produce heat and electric power. From the simplest stoves and boilers to more advanced pre-treatment systems with emission controls, combustion systems vary. Combustion has the lowest energy recovery potential compared to the other processes, pyrolysis, and gasification, but it is still a viable option for on-site energy generation. By co-occurring thermal conversion technologies, such as pyrolysis, gasification, and combustion, to create an integrated multiplier process, the most efficient use of FVW for bioenergy creation can be guaranteed.

3.3 Fermentation techniques: ethanol, methane, hydrogen, and other biofuel production from fruit and vegetable waste

More than that, fermentation techniques are critical for the valorization of fruit and vegetable waste by converting fermentable sugars and organic until to various biofuels: fermentation, ethanol, methane, hydrogen, and other valuable biochemicals. Ethanol fermentation is the conversion of sugars obtained from FVW into ethanol by anaerobic yeast and bacteria. This process includes the use of glucose, fructose, and other similar sugars produced by fruit and vegetable residues. FVW ethanol can be applied as a biofuel component to conventional gasoline or standalone fuel for transportation, thereby lowering greenhouse gas emissions and driving away from fossil fuels-domestic dependent. The second is methane fermentation, or anaerobic digestion, is the biochemical procedure where methanogenic microorganisms metabolize organic material in FVW to create methane and dioxide. The biogas combination consisted mostly to methane-causing as an energy source is renewal for heating and electrical power creation and as a vehicle fuel. Methane fermentation has two benefits: treating waste and retrieving energy by reducing environmental pollution and utilizing the FVW energy potential. The third one is hydrogen fermentation, or dark fermentation, which is the bio-process where FVW organic materials are converted to hydrogen gas and carboxylic acids by microbial [32]. This method, which works by hydrogen-producing germs under anaerobic conditions, offers a pathway for the biohydrogen production of FVW. Hydrogen is a versatile fuel source for multiple applications, ranging from fuel cells to commercial processes and transportation. Additionally, due to their specific microbial molecules, fermentation may provide FVW with other biofuels and biochemicals, including butanol, organic molecules, and carboxylic acid. Biobutanol, an emerging biofuel, is produced through the fermentation of sugars by Clostridium species. It has a higher energy content compared to bioethanol and can be used in gasoline engines without modifications, making it a promising alternative fuel. Carrot discard was found to be an effective raw material for acetone-butanol-ethanol (ABE) fermentation, achieving up to 76% sugar recovery and 7.4 g/L butanol concentration without pretreatment using a specific enzyme mixture, while hydrothermal pretreatment increased sugar recovery to 88% but slightly reduced butanol yield to 6.9 g/L [33]. Wang et al [34] demonstrated that direct butanol production from starchy food waste using Clostridium saccharoperbutylacetonicum N1-4, without saccharification or nutrient supplementation, yielded 12.1 g/L butanol, proving it to be a low-cost, efficient, and simple process. These biofuels and biochemicals have practical applications in the chemical sector, biorefineries, and the production of bio-based items, showcasing the potential of creating a sustainable bioeconomy through the fermentation of FVW.

4. Integration Strategies for Enhanced Bioenergy Production

Several integration strategies are important for enhancing bioenergy production from FVW such as resource utilization, energy recovery, and process optimization. One of the integration strategies is cascading utilization of FVW, which implies that the residue of one utilization process is used as a feedstock in the subsequent process, which helps to extract as much value as possible from the biomass. For instance, after the AD process to produce biogas, the digestate can be further processed by composting to produce soil-enhancing nutrients resulting in a closed loop of nutrient procession and increased soil productivity. Additionally, integration with other bioenergy production pathways offers synergy effects for enhanced overall efficiency and energy recovery. Thus, AD in combination with thermochemical conversion technologies like pyrolysis and gasification can create a biorefinery in which FVW is separated or fractionated into various bioenergy products, biochemicals, and nutrients amendments. The syngas could be used for heat and power production, while biochar from pyrolysis could be used as a soil ameliorant to enhance the soil structure and sequester carbon [35]. The integration of Anaerobic Digestion (AD), Hydrothermal Liquefaction (HTL), and Pyrolysis in Food and Vegetable Waste (FVW) processing creates a synergistic approach that maximizes efficiency and resource recovery. AD effectively handles high-moisture waste, producing biogas and digestate, while HTL converts wet biomass into bio-crude oil under high temperatures and pressures. Pyrolysis thermally decomposes dry organic materials into biochar, bio-oil, and syngas. An integrated process flow can pre-treat and separate waste for optimal processing by each technique, resulting in multiple valuable outputs such as biogas, bio-oil, biochar, and syngas. This approach minimizes environmental impact, reduces landfill use, and provides diverse revenue streams, though it requires careful consideration of investment costs and operational complexity. Co-digestion strategies also improve biogas production and process stability making use of animal manure food, waste, and energy crops. There is a high diversity of feedstock that improves nutrient balance and substrates for the bios to increase biogas production minimize inhibitory effects. Integration with other industrial processes, including wastewater treatment, will increase energy generation and resources from FVW.

The bioenergy generation plants could be co-located with food processing plants or municipal wastewater treatment, which could provide waste heat, water, and nutrients for AD or other bioenergy conversion processes. Therefore, the integration strategies for increased bioenergy from FVW include cascading utilization, synergy between bioenergy pathways, co-digestion, and integration with other industrial processes. Table 3 explains about the Integration Strategies for Enhanced Bioenergy Production.

4.1 Co-digestion of fruit and vegetable waste with other organic substrates

The co-digestion of FVW with other organic substrates offers a potential path for improving efficiency and stability of biogas production during the anaerobic digestion process. When FVW is co-digested with compatible substrates, such as animal manure, food waste, agriculture waste, or energy crops, the nutrient balance improve, and the substrate diversity and microbial populations in the digester increase. The effectiveness of co-digestion is based on the synergy between different substrates contributing distinct bio-compositions and microbial communities to the digester. FVW, with its high-carbohydrates that degrade rapidly, complements high-nitrogen substrates such as manure by supplying extra carbon and counterbalancing ammonia inhibit. Moreover, co-digestion with high-fat materials such as the food waste of grease trap waste improves biogas yields by offering a substrate rich in lipids. Co-digestion improves the economics of AD processes by increasing biogas yields and reducing the cost of process operation [39]. FVW co-digestion with common substrates such as municipal organics and agricultural waste enhances the use of existing infrastructure and streamlines feedstock supply. Moreover, stripping generates multiple revenue sources through support for renewable energy and value-added waste disposal. However, successful co-digestion implementation needs to consider key factors in feedstock characteristics, ratio mixing, process monitoring, and reactor configuration. From C/N balance to optimal pH and conditions, to inhibitory agents control, it is vital to maintain conditions that encourage higher biogas yields and stability [40]. Likewise, substrate compatibility and mixing assessment play a significant role in reducing process disturbances and increasing biogas. Generally, co-digestion of fruit waste with compatible substrates is a promising means to increase biogas yields and improve renewable bioenergy technology waste management practices.

Table 3. Integration Strategies for Enhanced Bioenergy Production

Integration Strategy	Description	Benefits	References
Co-digestion	Combining fruit and vegetable waste with other organic substrates	Diversifies feedstock, enhances biogas yield	[36]
Integrated Biorefinery	Utilizing multiple conversion pathways to extract maximum value	Maximizes resource recovery, minimizes waste	[37]
Combined Heat and Power	Simultaneous generation of heat and electricity from bioenergy production	Improves energy efficiency, reduces emissions	[38]

4.2 Combined heat and power (CHP) generation systems

Combined heat and power generation systems represent a viable and sustainable modality for the exploitation of FVW for bioenergy production. CHP, or cogeneration, is a method of generating electricity and useful heat from coincident generation utilizing an identical fuel source, such as biogas from the anaerobic fermentation of FVW. Such an approach to integrated energy generation is facilitated through CHP technologies, which results in the optimal exploitation of energy flows and resources [41]. This approach represents a synergistic valorization strategy for FVW. In a CHP system, biogas produced through the anaerobic fermentation of FVW is employed to operate a generator, which burns the fuel to generate electricity. Simultaneously, the waste heat generated by the decomposition is stored and employed in other thermal applications, such as warm water production. Through the optimal harvesting of both process electricity and thermal energy, CHP systems can achieve overall efficiencies of over 85 percent, significantly superior to conventional power generation. The implementation of CHP systems offers numerous practical benefits in the context of FVW valorization. Firstly, it improves the economic feasibility of bioenergy generation via the generation of electrical and thermal energy that can be used on-site or offered to the grid and surrounding facilities. This allows for income from electricity generation even as energy prices decrease and dependence on grid-delivered process heat is reduced. Moreover, the installation of CHP systems decreases greenhouse emissions by changing the fuel utilized to generate electricity and process heat from meticulously burned to an FVW-derived biogas. Finally, the decentralized nature of the CHP system implies that it may be implemented at the site of the FVW generator [42].

4.3 Synergies between bioenergy production and waste management strategies

Maximizing resource recovery, energy generation, and environmental benefits from fruit and vegetable waste by the synergies between bioenergy production and waste management are essential. Dissimilar bioenergy production processes combined with waste management ensure the establishment of an integrated system whereby organic residues are converted by researchers into valuable energy carriers. These benefits are obtained from sustainable and renewable waste management and energy production systems [43]. A key synergy between bioenergy production and waste management is utilizing FVW as a feedstock in generating bioenergy. This energy achieves organic waste out of the land fields and reducing methane gas through anaerobic degradation in the land middle. The generation of biogas through anaerobic degradation applies of FVW as cost feed source to produce methane and carbon dioxide biogas or renewable energy source. It also helps stabilize organic matter and reduce the amount of pathogen in the digestate. In general, AD synergetic FVW improves waste management in various ways ranging from reducing waste to minimal, reducing environmental pollution, and renewable energy. Furthermore, is the bioenergy production synergy with waste management expand to the use of byproduct and remaining bioenergy in FVW. Data use for AD remaining is utilized as a closed nutrient material in the land due to the high rate of nutrient response to the sand for soils. Biochar is bioenergy use and is a charcoal type for recharging the soil. An integrated approach for generating bioengineer through the process of waste resorting to waste heat, water and nutient. Therefore, the conditioner may minimize the lack of production costs and environmental piluton for space utilization. The bass generation of bioenergy through generation and waste target efforts enhances the efficient minimization process while reduction in the remaining value creation is maintained. In conclusion, tolerance of FVW by integration of biogenerator production does not only tackle the development process well as well as submissive the bio reduction process overturns organic into valuable issues. Finally, tolerance of FVW by capitalization of bio-sensitive value creation helps in advancing societies into suitable ways.

5. Process Optimization and Enhancement

The process optimization and enhancement are essential to achieve the optimal efficiency and effectiveness of FVW valorisation for bioenergy production. This can be achieved through optimization strategies that target various critical areas of bioenergy conversion processes, such as feedstock pre-processing, reactor design, operational parameters, and product recovery to maximize energy yields, minimize costs, and reduce environmental impact. For example, feedstock pre-processing involves feeding pre-treatment techniques to increase the accessibility and digestibility of FVWs constituents [44]. The mechanical size reduction, for example, commonly used, includes shredding and grinding and increases the surface area for microbial access to the organic matter during anaerobic digestion or enzymatic hydrolysis. Thermal pre-treatment methods, like microwave or steam explosion, are also critical in the disruption of the lignocellulosic structure of FVW. This eases the enzymatic digestibility and throughput, leading to high biogas production rates. Moreover, optimization of reactor design and operating conditions is also critical in achieving maximum bioenergy yields and process efficiency. For example, the temperature, pH, HRT, and OLR in any AD system must be well managed to ensure optimal microbial activity and biogas production rates. Similarly, thermochemical conversion such as pyrolysis is highly dependent on reactor temperature, residence time, and gas flow rate, which influence product yields and quality [45]. Furthermore, producer gas and biochar from gasification systems can also be enhanced as valuable byproducts and residues. Integrated holistic monitoring and control systems with data analytics and modeling systems improve real-time optimization and decision-making in the process. They include the integration of sensors, automation, and control algorithms to allow precise and timely management of process parameters and the early detection and prevention of deviations enhancing the stability and reliability of the system. Therefore, process optimization is critical in achieving maximum quality and quantity of bioenergy products, thereby guaranteeing a sustainable and safe circular bioeconomy. Table 4 talks about the Process Optimization and Enhancement.

5.1 Optimization techniques for improving bioenergy yield from fruit and vegetable waste

Optimization techniques are essential for maximizing bioenergy yield from FVW, leading to efficient use of organic resources and promoting sustainability. Different optimization approaches can be applied to ensure maximum bioenergy yield from FVW, including feedstock selection, preprocessing methods, process parameters, and reactor optimization. To begin with, feedstock selection is a critical factor in maximizing bioenergy yield from FVW. Composition of feedstock can be optimized by combining different types of fruit and vegetable residues that possess differences in biochemical profiles.

This enhances substrate availability and promotes microbial activity in bioenergy conversion processes. Moreover, feedstock selection should consider seasonality, where feedstock availability and quality depend on fruit and vegetable production schedules [48]. Preprocessing techniques are vital for enhancing the accessibility of FVW constituents and improving digestion. Mechanical preprocessing methods such as size reduction, milling, and grinding increase the surface area and the material's accessibility to microbes in anaerobic digestion or enzyme in enzymatic hydrolysis. there are the least important among thermal pretreatment approaches. The other thermal pretreatment methods such as microwave heating and steam explosion that cause damage to FVW lignocellulosic structure also disrupts the wood material digestibility and the biogas production rates. Optimization of process parameters is another critical aspect of bioenergy yield from FVW. Parameters such as temperature, pH, HRT, and OLR should be optimized to maximize microbial activity and biogas production in AD while minimizing process inhibition and substrate degradation. Similarly, thermochemical process parameters, such as reactor temperature, residence time, and gas flow rate, should be optimized to influence yields and product quality. Additionally, reactor design should be optimized to enhance bioenergy yield from FVW. Design processes involve appropriate mixing, heating, and retention that enhance substrate conversion and product recovery. Furthermore, advanced monitoring and control systems should be integrated to facilitate real-time optimization and decisions that enhance process stability and reliability. In conclusion, optimization techniques are essential for achieving maximum bioenergy yield from FVW and promote sustainable practices and a circular bioeconomy. Continued application of optimization strategies will facilitate synergistic valorization of FVW.

5.2 Pre-treatment methods to enhance digestibility and conversion efficiency

Pre-treatment methods are critical for improving the digestibility and conversion efficiency of fruit and vegetable waste for bioenergy production. They help to degrade complex organic compounds and promote the accessibility of substrates in later conversion stages.

Table 4. Process Optimization and Enhancement

Process Optimization and Enhancement	Examples	Process Optimization and Enhancement	References
Feedstock Selection	Utilizing diverse fruit and vegetable residues	Feedstock Selection	[45]
Preprocessing Methods	Mechanical (shredding, grinding), chemical, and biological	Preprocessing Methods	[46]
Process Parameters Optimization	Temperature, pH, Hydraulic Retention Time (HRT)	Process Parameters Optimization	[47]

A wide range of pre-treatment techniques can boost the efficiency of bioenergy conversion from FVW, classified into physical, chemical, and biological methodologies. Physical pre-treatment approaches are intended to break down the physical barriers of FVW, which increases the surface area and reduces the particle size for enzymatic hydrolysis. Mechanical treatment, namely shredding, grinding, and milling, physically disintegrates FVW into smaller particle sizes to facilitate microbial digestion and enzymatic saccharification Furthermore, extrusion and ultrasound-assisted pre-treatment use escalated physical forces to disrupt the cell walls and increase substrates digestibility. Chemical pre-treatment applies the chemicals to the FVW to destroy the lignocellulosic barriers and solubilize the organic matter [49]. Acid hydrolysis, alkali treatment, oxidative chopping methods change the chemical nature of FVW and hydrolyze the lignin and hemicellulose content and release fermentative sugars. Moreover, the combination of the above chemical pre-treatment methods may have a synergetic effect on the efficiency of enzymatic hydrolysis and microbial digestion. A biological process utilizes microorganism or enzymes to disintegrate complex organic molecules and makes substrate accessibility. Microbial fermentation, enzymatic hydrolysis, or microbial consortia pretreatment use the metabolic activities of microorganisms to disintegrate the lignocellulosic biomasses and solubilize the organic compounds. Co-culture and inoculation with FVW use enzyme-producing microorganisms and enhance the pre-treatment efficiency, thereby promoting bioenergy production. In conclusion, pre-treatment is essential in bioenergy production from FVW. Pre-treatment methods in enhancing the digestibility and conversion efficiency of fruit and vegetable waste (FVW) for bioenergy production. Hence, by optimizing pre-treatment conditions and selecting suitable methodologies, synergistic valorization can be attained to realize sustainable waste management and circular bioeconomy through enhanced resource recovery and energy generation.

5.3 Enhancement of biogas quality and yield through process optimization

Process optimization for biogas production from fruit and vegetable waste. Achieving an optimal process in anaerobic digestion as a way of sequestering economically valuable biogas from fruit and vegetable waste is critical for enhancing both the quality and yield of the biogas. These are indicated to be the major aspects that affect biogas production and quality, and process optimization allows to boost them. Process optimization primarily refers to enhancing major factors that influence the biogas production and quality, as highlighted earlier, including the substrate characteristics, reactor design, operational parameters, and microbial activity. Substrate optimization. substrates must be optimized for biogas production quality from fruit and vegetable waste [50]. This should be achieved by ensuring diverse FVW with a favourable biochemical composition that contains carbohydrates, proteins, and lipids essential in providing a nutrient supply for microbial consortia. Moreover, the feedstock should maintain a balanced carbon-to-nitrogen (C/N) ratio to enhance microbial growth and activity that raises biogas production rates and raises methane content in the stream. Optimizing reactor design, operational parameters. Reactor design and operational parameters are necessary to optimize biogas production system quality from FVW. Factors such as temperature, pH, HRT, OLR, and mixing intensity affect the microbial activity and biogas production rate in AD systems. Mesophilic or thermophilic temperatures and near-neutral pH and controlled OLR conditions promote HRT conditions provide optimal conditions for microbial consortia to degrade organic matter and produce biogas. Apart from the substrate and reactor, enhancing microbial activity is essential in improving biogas quality and yield. Microbial inoculation and co-digestion with other organic substrates improve biogas quality and yield during the acclimatization of digester microbial communities in the hydrolysis and fermentation processes. Microbial community structure in the microbial substrate plays a crucial role in improving environmental conditions in biogas as above. Process optimization, therefore, delivers a synergistic impact on biogas production quality and yield from FVW to increase resource recovery, energy conversion, and environmental sustainability [51].

6. Techno-Economic Analysis and Feasibility

Techno-economic analysis (TEA) and feasibility assessments are essential parts of the evaluation of synergy-based valorization strategies of fruit and vegetable waste in bioenergy. TEA involves the systematic analysis of technical and economic components to determine the commercial viability, profitability, and return on investment of bioenergy as a feedstock using FVW. The first step of TEA involves the description of the technical elements of the process of bioenergy production, such as the feedstock supply potential and the technological conversion process, efficiency, and energy quantity. It is then followed by a detailed techno-economic model that estimates the costs and capital outlays of FVW saving, preprocessor, conversion, and energy generation [52]. Modeling techniques like process simulation and parametric analyses, and value maximization must be used to identify optimized scenarios and recommendation conditions. Evaluation of direct revenues from the sale of bioenergy or Byproducts and other indirect sources, such as carbon credit or government incentives is another cost consideration in TEA. Life cycle assessment is another consideration for TEA supporting magic techniques, evaluating and quantifying environmental impacts to determine the sustainability of bioenergy from FVW production. It evaluates the impact on the environment and consumption of resource and carbon emission every stage from the raw material to conversion to offer insights into the transportation means [53]. Feasibility and viability assessments consider market demand, regulation, risk angles, and stakeholder analysis. Community involvement is crucial to understanding and evaluating social considerations and obtaining essential permits. Personality and scenario-based models of human life. These assessments facilitate the vital role of the systematic government and the administration and regulation of bioenergy utilizing FVW and consideration of TEA and MA results. Figure 3 shows the Techno-Economic Analysis and Feasibility.

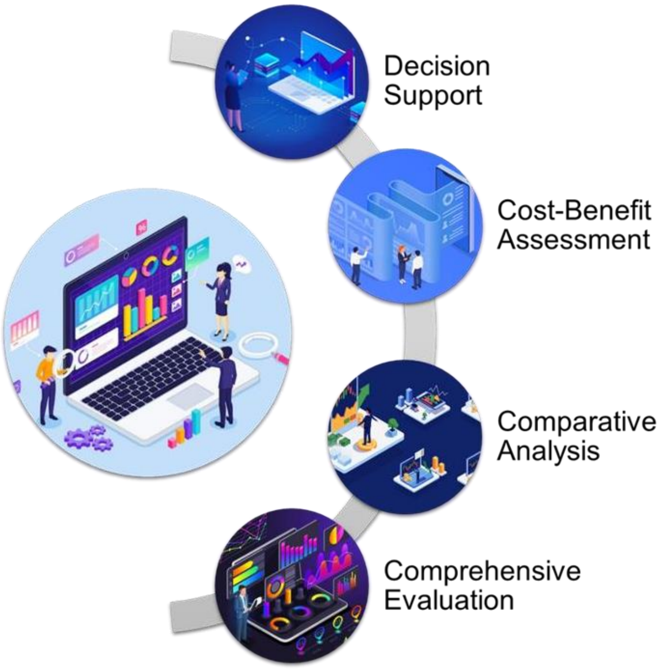

Figure 3. Economic Viability and Technical Feasibility Analysis

6.1 Economic feasibility of bioenergy production from fruit and vegetable waste

Economic feasibility analysis is instrumental in determining the viability and sustainability of synergistic valorization strategies through the production of bioenergy from fruit and vegetable waste [54]. The economic feasibility analysis considers the costs and benefits associated with the production of bioenergy from FVW and related processes. Cost aspects considered include feedstock, capital and operating costs, conversion technology, market prices, and regulatory incentives. Capital costs refer to the cost of establishing bioenergy production plants, which include infrastructure, equipment, and labor costs. The costs vary based on the scale and complexity of the bioenergy production process since larger scales benefit from economies of scale. Other considerations include operating costs associated with feedstock procurement, preprocessing, the process of energy generation, maintenance, and labor costs. Cost-related factors are analyzed to deduce the overall cost of bioenergy production from FVW. Revenue aspects are also analyzed considering the income streams from bioenergy sale, by-product valorization, carbon tax credits, and potential government incentives or subsidies. Market analysis is needed to determine the market demands, pricing trends, and the nature of competitors. Potential revenue streams arising from by-products such as digestate, biochar, or biochemical enhance the economic viability of bioenergy production from FVW. Sensitivity analysis and risk factors used in economic feasibility analysis and help identify factors that affect project profitability and the ability to withstand market volatility, regulatory variation, and other risks. Sensitivity analysis helps quantify the effects of volatility on feedstock and energy prices and operating costs. Risk factors and assessment allow decision-makers to evaluate and manage risks and develop responses to prevent loss of funds. Moreover, the social and environmental benefits of bioenergy production from FVW, which include waste recycling, greenhouse gas reduction, and job creation among others, also increase overall feasibility [55]. Proper evaluation of costs, benefits, and risks enables policymakers and investment decisions that promote bioenergy production from FVW.

6.2. Cost-benefitanalysis of different valorisation pathways

Cost-Benefit Analysis of Valorization Pathways. A cost-benefit analysis of valorization pathways is essential to access the economic feasibility and sustainability of the event synergistic valorization pathways of FVW for bioenergy production. The cost-benefit analysis costs and benefits financial assessment of valorization costs, anaerobic digestion, Fermentation, Thermochemical conversion, and Synergistic valorization pathways to select the best events and visualize the economic feasibility. The cost part of a CBA consists of the capital investment, operational expenses, and maintenance cost of each valorization pathway. The capital investment includes the cost of infrastructure, equipment, and labor required for establishing and running bioenergy production facilities. Meanwhile, operational expenses consist of feedstock, preprocessing, conversion, energy generation and byproduct handling costs. The latter is further supplemented by maintenance expenses, comprising the repair and replacement cost of equipment to ensure the continuous operation of bioenergy facilities. In turn, benefits, including revenue from bioenergy sales, byproducts and carbon credits sales, and potential government incentives and subsidies are examined [56].

For example, bioenergy revenue directly depends on energy prices, the current market situation, and the level of competition. Byproducts income involves the sales of digestate, biochar, or biochemical. It could be a significant part of the revenue and, thus, a determinant factor for the existence of valorization pathways. Finally, carbon credits and renewable energy certificates acquired through FVW bioenergy generation may bring additional revenue and increase the economic feasibility of valorization pathways. In addition, the CBA should encompass social and environmental benefits manifestation, such as waste utilization, GHG emissions reduction, and new job creation, to contribute to the CBA's value. by the incorporation of these perspectives results, the decision-makers could avoid biased decisions and choose the most socially and economically beneficial valorization pathways for further promotion. Collectively, a CBA of different valorization pathways for FVW bioenergy production is crucial for the development of economically feasible and sustainable strategies to promote resource recovery and energy generation, as well as the environmental benefits of the bioeconomy circles.

6.3 Market potential and economic incentives for investment in bioenergy projects

Another critical step in the analysis of commercial feasibility and desirability of synergistic valorisation is to assess the market potential and economic incentives for bioenergy projects based on fruit and vegetable waste. Market dynamics, demand-side factors, regulatory considerations, and financial incentives are important sources of information for identifying opportunities and mitigating risks associated with bioenergy investment. The market potential for bioenergy projects based on fruit and vegetable waste FVW consists of expected demand for energy production, mandatory renewable targets, waste management legislation, and consumer preferences determination [57]. People are concerned with environmental matters and the development of alternative sources of energy, which is a favourable factor for bioenergy development. Furthermore incentivized production regimes, such as the Feed-in Tariff, Renewable Energy Certificates, and Carbon Pricing, lead to investment in bioenergy production from FVW. Economic incentives include government grants, subsidies, tax deductions, and below-market loans either stimulate bioenergy project formation or do not bring the next bioenergy development stage any closer. Incentive programs designed to promote renewable energy and manage waste flows attract more investment in bioenergy production facilities and machinery. Partnerships with research institutes and industry associations and funding from financial institutions help secure capital, technical assistance, and market access to ensure the economic viability of bioenergy projects. Additionally, competitive analysis and market research help identify niche markets, value-added products, and synergistic partners to maximize FVW-based bioenergy projects' economic potential. Collaborating with waste producers, energy suppliers, regulators, and consumers will achieve market-oriented solutions to meet specific needs and add economic value. In conclusion, evaluating the market potential and economic incentives for investing FVW-based bioenergy requires an understanding of market structures, regulations, and financing instruments. Market opportunities and economic incentives can maximize the economic potential of FVW to develop bioenergy artificially while ensuring environmentally sound waste management.

7. Future Perspectives

Overall, future perspectives on the synergistic valorization of fruit and vegetable waste for bioenergy production are promising. Continued breakthroughs in technology, policy frameworks, and sustainable development are redefining the bioenergy research landscape. Advancement in technology is improving waste-to-bioenergy conversion processes that increase yields of bioenergy and other value-added products. Developments such as advanced pretreatment, enzymatic hydrolysis, microbial consortia engineering, and biorefinery concepts increase biogas yields, produce high-value biochemicals and optimize resource utilization. Additionally, process monitoring, control systems, and data analytics offer real-time information that improves the efficiency and reliability of bioenergy production. Policy action is driving renewable energy, waste management, and circular economy in boosting bioenergy projects from FVW [58]. Incentives in the form of renewable energy targets, landfill diversion mandates, government subsidies, and regulatory policy are enhancing investment in FVW valorization. Initiatives in bilateral and multilateral climate agreements are enhancing renewable energy as a low-carbon source and a solution to the environmental concern in organic waste. Integration of bioenergy with sectors enables collaboration and optimization of resources. Co-biorefinery, co-digestion, and power-to-gas technology ensure biomethane is maximized. Collaboration and synergies give the maximum advantage to bioenergy production. In conclusion, future perspectives in FVW are characterized by technology, policy support, and collaboration. Further research, investment, and cooperation are necessary to accomplish the potential of FVW as essential resources.

7.1 Remaining challenges in fruit and vegetable waste valorization for bioenergy production

The fruit and vegetable waste valorization for bioenergy production has made significant advancements; however, the remaining challenges with feedstock variability, process stability, economic feasibility, and social acceptance hinder the optimization and wide implementation of synergistic valorization strategies. Feedstock variability, which affects the process performance and biogas yield, imbalance inhibitory compounds, and process stability, as well as the high capital costs and uncertain revenue streams, and social and environmental considerations, are united by the need to develop appropriate strategies for reduce these effects, optimize process parameters, and enhance public perception and acceptance. For instance, addressing high feedstock variability involves developing suitable strategies to compensate for its effects and optimizing the process parameters, process imbalance requires developing a monitoring and control system, robust pretreatment methods, microbial acclimation to substrata, while financial risks associate with high capital costs and uncertain revenue streams can be reduced through the development of a comprehensive revenue model based on by-product sale, policy incentives and utilizing the latest advances in financing and investment for renewables. Similarly, social acceptance can be achieved by developing sustainable waste management practices and engaging the public through educational programs [59]. The fruit and vegetable waste should be realized as an opportunity for sustainable bioenergy production and waste management, and the ambitious goals can only be achieved through collaboration and rigorously conducted research.

7.2 Research gaps and opportunities for future advancement

Although substantial progress has been made in recent years in the field of the synergistic valorization of fruit and vegetable waste into bioenergy production, a number of research gaps and opportunities for further advancement still exist. Understanding microbial dynamics and metabolic pathways during FVW valorization such as anaerobic digestion process remains key research gap. Although much of the progress has been made in the characterization of microbial communities and their functions as far as organic matters degradation is concerned, there is a need to delve further into the microbial dynamics and substrate components in different feedstock of FVWs. Similarly, research on the effect of process conditions on the microbial community structure and function are still-needed aspect. As a matter of fact, understanding how temperature, PH, and the composition of the substrate can contribute to optimizing biogas production efficiency and process stability is an important aspect [60]. Enhanced pretreatments method remains a big research opportunity so far. The methods are concerned with tightening the digestibility of FVW's functional components discussed above. While mechanical and chemical methods have shown promising results in improving substrate accessibility enzymatic, microbial, and co pretreatment and combinations among other methods have not thoroughly investigated. Meanwhile, developing new energy-efficient, cost-effective, and environmentally friendly methods for treating recalcitrant components in FVWs could revolutionize the field and unlock their energy potential. Lastly, comprehensive techno-economic and environmental assessment of FVW synergistic valorization strategies remains a big opportunity. Approaches involving LCA and CBA sustainability metrics should consider the entire value of the value chain, from feedstock collection to bioenergy and by-product utilization. Innovative pathways, such as integrated biorefinery concepts, co-digestion with other wastes, and combined bioenergy production with other renewable sources for maximum resource recovery and environmental sustainability, should also be explored [49]. Interdisciplinary collaboration, innovative thinking, and holistic waste management approaches are essential for developing sustainable and renewable energy solutions for bioenergy production from FVWs. Thus, for now, researchers must continue to work to ensure progress towards efficient, economically beneficial, and environmentally sustainable bioenergy production from FVWs is achieved.

7.3 Potential technological innovations and emerging trends in the field

Consequently, within the ambit of synergistic valorization of fruit and vegetable waste for bioenergy production, potential technological innovations as well as emerging trends, offer a glimpse into a more efficient, sustainable, and economically viable process. The first critical technological innovation that portends efficiency is the adoption of advanced pretreatment methods designed to improve the digestibility and conversion efficiency of FVW components. Various emerging pretreatment techniques such as microwave-assisted processing, ultrasound pretreatment, and plasma treatment may be utilized to disrupt the lignocellulosic structure of FVW, allowing for more enzymatic access and biogas yield [61]. These advanced pretreatments would alleviate the sluggish feedstock difficulties linked with recalcitrant FVW components and catalyze the utilization of biomass with potential for bioenergy production. In addition, the recent trend of integrating novel biorefinery concepts into FVW valorization pathways is emerging. Biorefinery concepts focus on optimizing and enhancing resource recovery and value from FVW by simultaneously generating bioenergy, bioseeds, and bioproducts from other wastes. For instance, biorefinery concepts could link anaerobic fermentation to various post-treatments such as microbial or enzymatic transformation for the production of biofuel, platform chemicals, and value-added by-products from FVW. This would enhance the economic process and output efficiency. Finally, the recent trend of technological advances in monitoring processes through control systems and data analytics is catalyzing innovation. The integrated sensor network and platforms and artificial intelligence -based, predictive modeling, process optimization, and decision-making centered on bioenergy manufacturing process. These technological advancements in process parameters optimization, promote early detection capability, process efficiency, and continuous adjustment to FVW valorization system's performance and reliability. Moreover, the disruptive trend is the rise of decentralized and modular systems of bioenergy. This trend facilitates distributive energy production, waste management, and community resilience. The small-scale anaerobic digesters, portable biorefinery units, and microgrid integration present scalable and flexible solutions to FVW valorization approaches. _decent, particularly in rural and remote regions that cannot access central supportive infrastructure. In conclusion, potential technological innovations and emerging trends in the field of synergistic valorization of FVW for bioenergy production offer hope for the future to progress sustainability waste management, renewable energy, and resource recovery. By utilizing these technological advancements and trends, relevant stakeholders will successfully maximize the potential of FVW as a sustainable resource to address energy, environmental, and sociocultural challenges.

8. Conclusion

This demonstrates the he potential of synergistic valorization approaches to produce bioenergy from fruit and vegetable waste (FVW). By exploring various pathways such as anaerobic digestion (AD), thermochemical conversion (TC), and fermentation, as well as integrated biorefinery (IB) concepts. By optimizing waste-to-energy conversion and producing valuable by-products, this integrated approach contributes significantly to several United Nations Sustainable Development Goals (SDGs). FVW emerges as a valuable feedstock with abundant organic content for renewable energy (RE) and bio-based products. Despite promising outcomes, challenges such as feedstock variability, process irregularities, economic feasibility, and social acceptance persist. Interdisciplinary research, technological advancements, and policy support are essential to overcome these barriers. Addressing knowledge gaps, optimizing processes, and deploying new RE approaches are necessary steps. Engaging stakeholders, promoting circular economy principles, and integrating bioenergy with other RE activities can enhance system sustainability and resilience. Efficient valorization and a culture of innovation can drive the transition to a sustainable and resource-efficient bioeconomy model.

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Yes

Competing Interests

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