

Research Article

Converting Food Waste into Energy and Valuable Products Through Microbial Processing

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Abstract

Food waste is one of the most pressing global challenges due to its significant environmental, economic, and social impacts. Nearly one-third of all food produced for human consumption is lost or wasted annually, contributing to greenhouse gas emissions, resource depletion, and food insecurity. This study investigates the microbial processing of food waste as a sustainable approach for transforming organic residues into renewable energy and valuable bioproducts. Various microbial and thermochemical conversion methods including anaerobic digestion, fermentation, pyrolysis, gasification, and composting are examined for their ability to produce bioenergy, biogas, bioethanol, biochar, bioplastics, single-cell proteins, and nutrient-rich compost. These technologies not only reduce the volume of waste but also enhance circular economy practices by converting waste materials into resources that support agriculture and industry. Furthermore, advances in metagenomic tools and microbial biotechnology have improved understanding of microbial communities and enhanced the efficiency and yield of bioconversion processes. Integrating these biological and engineering innovations can optimize waste valorization systems, leading to reduced greenhouse gas emissions, improved nutrient recycling, and sustainable energy generation. Overall, microbial processing offers an eco-friendly and economically viable strategy for global food waste management, aligning with the United Nations Sustainable Development Goals to reduce waste and promote renewable energy use. The outcomes of this research highlight the potential of microorganisms to convert food waste into bioenergy and bioproducts, thereby supporting environmental preservation and resource recovery.

Keywords

Food West, Anaerobic Digestion, Sustainability Energy Generation, Waste Management

1. Introduction

Food waste consists of solid materials emanating from human and animal activities, normally regarded as unwanted or not useful to be eaten. This encompasses all sources, classifications, compositions, and characteristics of waste, which can be divided into four main categories: municipal waste, industrial waste, hazardous waste, and hospital waste [1]. Each year, humans waste a staggering 1.4 billion tons of

food. Despite global initiatives aimed at reducing hunger, there remains a lack of motivation to reverse this concerning trend [2]. Various management practices exist for handling solid waste from food production, and because these wastes have high nutrient levels and water content, and may encourage bacterial growth and fermentation, odors and other environmental problems may arise. Recent studies indicate

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that processing food waste with microorganisms to create innovative products could effectively tackle global food shortages while also alleviating the negative impacts of climate change [3]. Recycling food waste involves repurposing discarded materials to produce either the same product or other usable goods. After paper, food waste represents the largest segment of the global waste stream, accounting for 14.5% of all discarded materials [4]. Nearly all items that end up in landfills, including food, are recyclable. A study by the Food and Agriculture Organization of the United Nations revealed that food is wasted at every stage of production, from agricultural output to consumer levels. Regardless of where food waste occurs, it is often disposed of in landfills or processed to address environmental concerns. Each year, between 1.3 and 1.6 billion tons of food—including fresh produce, meat, baked goods, and dairy products—are lost throughout the supply chain. In densely populated regions, food waste can pose significant health risks, highlighting the need for effective management [5]. Landfilling food waste is not appropriate, as producing that food consumes valuable energy and nutrients leading to additional costs and environmental pollution. Various studies have explored methods to generate energy from food waste, including incineration, anaerobic digestion, and using food waste as livestock feed to sustain the nutrient cycle. A promising approach involves using food waste as a raw material for cultivating microorganisms [6]. This technique allows for the recycling of waste materials containing carbon, nitrogen, and phosphorus through their absorption into biomass and the metabolites of microorganisms, facilitating their use in producing chemicals, various compounds, and energy. Given the rising levels of food waste, the environmental concerns associated with it. Similar to the production of methane, which causes climate change, and the rich organic and nutrient composition of these materials, this article explores innovative applications of microorganisms in processing food waste, illustrating how these biological agents can transform waste into valuable energy and new

products.

2. Main Causes of Food Waste and Waste Production

Food waste arises from a variety of unexpected factors. While it's understandable that individuals may not fully consume large portions of food in restaurants, at retail outlets, or as consumers, other less apparent causes are tied to agricultural practices, food safety standards, and consumer behaviors [7]. Reports from Kenyan farmers indicated that they lost their crops in 2020 due to locusts. The last time locusts swarmed at such a scale, between 2003 and 2005, it resulted in \$2.5 billion in crop damage. Locusts are mostly killed by pests; therefore, improving access to pesticides is one way to reduce food waste and assist small-scale farmers [8]. Besides natural causes, personal preferences also contribute to food waste. Research findings show that buyers tend to avoid purchasing "ugly produce." One-fifth of food products with surface blemishes, unconventional growth patterns, or unique colors are discarded by grocery stores [9]. This indicates that high-income countries contribute to food waste at the retail level in its early stages, and the Food and Agriculture Organization is unable to mitigate this wastage effectively. Climate change also plays a role in food waste and food insecurity by making planting and harvesting cycles less predictable. Unseasonal frosts, early springs, and a range of other climate variations significantly impact the prices farmers set for their products and their ability to predict the optimal timing for planting and harvesting [10]. The issues may be interrelated by virtue of supply and demand problems. This is where spoilage of goods is often caused by transportation, order, or inadequate storage facilities. Meanwhile, very well-intentioned regulations that are meant to protect people from food safety risks end up having an unintended effect of pulling food off the shelves before their best-by dates [11].

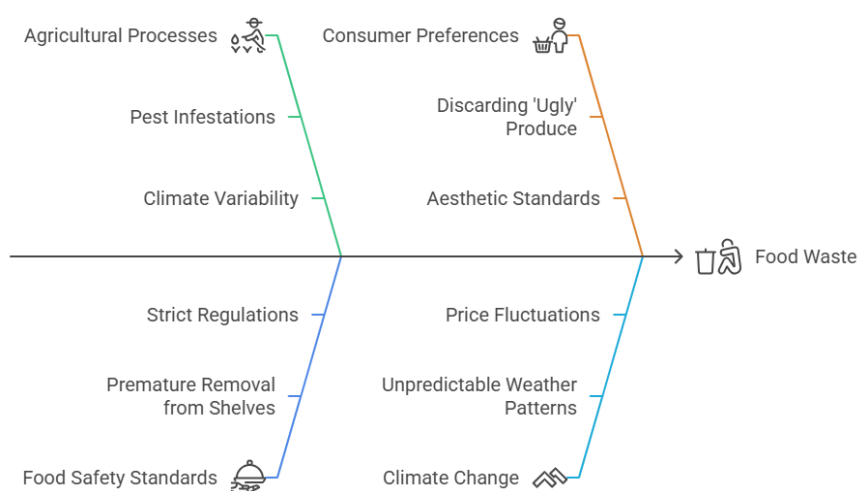


Figure 1. Different cycles in the creation of food waste.

Sustainable Food Management to Reduce Waste

The sustainable food management aims to minimize waste and avoid food losses that are not needed in the food chain. It is essential that food wastage is prevented through effective planning and that the different governments, food producers, retailers, and consumers collaborate among themselves. Food waste reduction is recognized as one of the key challenges that have been emphasized by the United Nations in the Sustainable Development Goals (SDGs) since they call for halving the overall food waste from retail and consumer levels by the year 2030. When achieved, this will lead to the improvement of supply chains, alleviate chronic poverty, assist the developing world, and help reduce emissions of greenhouse gases. Holistic food management considers waste from a systemic view. Food can become wasted during agriculture, harvesting, processing, sale, and consumption or during distribution. In order to prevent inefficiencies, each interconnected aspect of these should be analyzed and managed. Most of the waste comes from overuse of natural resources or from the goods not being sold. Management can save money for the food buyers and consumers by reducing waste, while the surplus food can then go to meet the needs of the poorer people. While governments play the greatest role, responsibility lies with businesses and consumers. Only if all of them put their weight behind it would a better, fair, and less-wasteful food system that makes the most efficient use of resources become a possibility [12-16].

3. Food Waste Recycling (Traditional and Modern Methods)

During 2020-2022, food wastage statistics by national levels indicate that around 9 million tons of food wastage was generated. This waste, in turn, causes considerable economic and social losses while contributing to the emissions of greenhouse gases, including CO₂ and methane from food wastage in landfills. The Ministry of Environment and Energy says that between 2016 and 2021, solid waste generated a total of the equivalent of 10 million tons of methane and CO₂, which indicates the huge potential of these compounds as contributors to global warming. Most of these emissions originate from decaying food wastage in landfills. However, food wastage has a range of impacts on many areas around the world. According to the World Institute, the United States and China are the leading carbon emitters in the world. The most effective reduction strategy for food wastage is simply to stop its generation entirely. It is not always possible to ensure all food products will be consumed, but food wastage could also be turned into useful compost, energy, and innovative products. Such applications encompass industries from pharmaceuticals to energy generation [17-19].

3.1. Recycling Through Traditional Methods and Burning Food Waste

Recycling through traditional ways has been a base block of waste management; this is one of the most sustainable methods in reusing materials and reducing environmental wastage. These methods include composting organic waste, reusing materials like glass and metal, and converting paper into new products. However, when it comes to food waste, an additional approach often considered is burning, particularly in waste-to-energy facilities. Burning food waste can serve as an alternative solution to reduce landfill usage while generating energy. Incineration of food scraps in controlled environments helps produce electricity or heat, contributing to renewable energy goals. However, this method is not without challenges. Food waste has high moisture content, which can reduce the efficiency of burning processes. Additionally, concerns about emissions and air pollution make it essential to adopt advanced technologies to minimize environmental harm. The combustion of biomass with a sufficient supply of air directly converts the chemical energy stored in the biomass into heat, which can be utilized to generate both mechanical energy and electricity. During combustion, organic waste oxidizes with oxygen at temperatures higher than its ignition point. Dry organic food waste with less than 50% moisture content (dry weight) is suitable for burning. Solid waste from food processing can either be directly combusted or first converted into liquid or gaseous fuels before burning. For example, the combustion efficiency of biodiesel derived from palm oil waste ranges between 56% and 66%. While traditional recycling methods emphasize resource recovery and sustainability, combining them with modern approaches could offer a more comprehensive solution to the growing global waste problem. By balancing these strategies, communities can work toward achieving a cleaner, more sustainable future [20, 21].

3.2. Modern Recycling and Thermochemical Waste Conversion

Thermochemical conversion utilizes heat to decompose materials, transforming them into gas, combustion products, or liquid fuels through processes such as liquefaction with water under high pressure. At elevated temperatures and in the presence of oxygen or air, organic food processing waste is broken down into smaller liquid or gas molecules. Organic waste can be converted into gaseous or liquid fuels when there is not enough oxygen or air. When oxygen levels are low, gasification takes place, resulting in a fuel gas that is mostly made up of hydrogen, carbon monoxide, carbon dioxide, and methane. In contrast, pyrolysis produces solid charcoal and liquid tar while operating in total oxygen deprivation. Different kinds of food processing waste can be transformed into useful energy sources like steam and

electricity using these thermochemical techniques. Anaerobic digestion and fermentation are two biological conversion techniques that are essential for turning waste into energy in addition to thermochemical processes. Through the process of anaerobic digestion, microbes break down organic waste to create biogas, which is a combination mainly composed of carbon dioxide and methane. Fermentation, using microorganisms like yeast, converts simple sugars into ethanol, offering another pathway for energy production. These waste-to-energy technologies not only help in managing food processing waste effectively but also contribute to reducing greenhouse gas emissions by diverting waste from landfills and replacing fossil fuels with renewable energy sources. Furthermore, the byproducts from these processes, such as biochar from pyrolysis or digestate from anaerobic digestion, can be used as soil amendments, improving soil health and fertility. The integration of thermochemical and biological conversion technologies can maximize the efficiency of waste utilization. For instance, a combined system could first extract energy-rich gases through gasification or pyrolysis, while the remaining organic material could undergo anaerobic digestion to produce biogas. Such hybrid approaches enable a more comprehensive conversion of waste into energy, minimizing residual waste and enhancing overall sustainability. As the global demand for renewable energy rises, advancements in these technologies are expected to further improve their efficiency, scalability, and economic viability. Research efforts are focused on optimizing process conditions, developing more robust microbial strains for biological conversions, and improving reactor designs for thermochemical methods. These innovations aim to make waste-to-energy systems more accessible and cost-effective for industries and communities worldwide. In conclusion, thermochemical and biological conversion methods represent powerful tools for tackling food processing waste while generating valuable energy and byproducts. By adopting these technologies, industries can move closer to achieving circular economy goals, where waste is no longer viewed as a burden but as a resource for sustainable energy production [22, 23].

Anaerobic Digestion of Food Waste

Anaerobic digestion operates as a methodology which reduces pollution while minimising pathogenic disease risks through its recovery of valuable materials from different forms of food waste including fruit and vegetable processing waste and meat processing waste as well as waste from slaughterhouses [24]. Anaerobic digestion is a biological process in which organic materials are decomposed in the absence of oxygen, producing biogas. Biogas, primarily composed of methane and carbon dioxide, can be used as an energy source, replacing fossil natural gas [25]. Methane constitutes 50% to 60% of the biogas by volume. If the biogas produced through anaerobic digestion is used for electricity generation, the overall conversion efficiency to

electricity is approximately 10% to 16%. One of the most important advantages of anaerobic digestion is that it can be used for organic waste with a pasty consistency as well as waste with high moisture content or in liquid form. Anaerobic digestion is a commercial technology and is widely applied for processing organic waste with high moisture levels (above 80-90%) [26]. In addition to producing methane for energy generation, anaerobic digestion of waste from food processing also destroys pathogenic bacteria present in the waste and reduces pollution emissions. Anaerobic digestion begins with the hydrolysis of compounds in organic waste. Proteins are hydrolyzed into amino acids. Lipids are broken down through beta-oxidation into long-chain fatty acids and glycerol [27]. Carbohydrates are hydrolyzed into sugars. Following hydrolysis, intermediates such as long-chain fatty acids, amino acids, and sugars are converted by fermentative bacteria into volatile fatty acids with three or more carbons, hydrogen, and carbon dioxide. Ammonia and sulfides are produced from the fermentation of amino acids. Some long-chain fatty acids, volatile fatty acids, and neutral compounds like sugars are converted by hydrogen-producing acetogenic bacteria into acetate, hydrogen, and carbon dioxide. Acetate, hydrogen, and carbon dioxide are entirely converted into methane gas and carbon dioxide by methanogenic bacteria. The retention time of waste inside the digester during anaerobic digestion can range from several days to a month. The generated gas can be used to produce electricity, and the residual heat can be recovered and utilized as a heat source in the anaerobic digestion system or processing lines. Anaerobic digestion can be employed for processing fish waste, slaughterhouse waste, fruit and vegetable processing waste, and wastewater from food processing [28, 29].

4. Metagenomic Tools and Techniques for Advanced Waste Processing

In a rapidly growing world, food waste and its management are among the major challenges facing our society due to the high risk they pose to human health and the increasing environmental burden. The strategic use of bioprocessing on food waste can lead to numerous social benefits. Energy production, such as biogas derived from food waste biomass, can be considered for easy storage and transportation [30]. Secondly, multilayered processing and management of food waste reduce harmful environmental impacts. The production of soil additives and liquid fertilizers from organic food waste directly encourages food waste management. Fragmented studies based on various 16S and 18S rRNA analyses have been conducted by researchers for waste management treatments, identifying microbial communities from all three taxonomic domains of the microbial world: Archaea, Bacteria, and Eukarya. In total,

4,133 methanogenic bacteria were classified under the Archaea domain, with Crenarchaeota and Euryarchaeota being the most prominent groups [31]. Methanogens exhibit significant morphological diversity: cocci (Methanococcus), spirilla (Methanospirillum), sarcina (Methanosarcina), rods (Methanobacterium), short rods (Methanobrevibacter), and filiform shapes (Methanotrix). Acetotrophic methanogens, which are obligate anaerobes primarily belonging to the genus Methanosarcina, play a role in converting acetate into methane and carbon dioxide [32]. The Methanobacteriaceae family has been associated with hydrogenotrophic methanogenic bacteria. Methanospaera stadmaniae and Methanobrevibacter wolinii are two main groups of hydrogenotrophic microorganisms involved in the anaerobic processing of fruits and vegetables [33]. Understanding the relationship between taxonomic and functional diversity and species richness can be key to a better understanding of ecosystem performance in processing food waste. Molecular methods such as PCR, RFLP, microarrays, and sequencing have been utilized in waste management. However, these methods have specific limitations in describing the functional aspects of large-scale ecological systems. Recently, metagenomics obtained through NGS has demonstrated the potential to describe the functional characteristics of agricultural soil microbial communities on a large scale. Applying these approaches to food waste management can enhance our understanding of treatment processes and improve the quality of treatment and management products. By exploring available microbial resources and strategically employing advanced metagenomic techniques, microbial communities can be utilized more efficiently in food waste management [34].

5. Recycling and Producing New Products from Food Waste

5.1. Compost Production from Food and Agricultural Waste

One of the best and simplest solutions for utilizing organic waste and recycling food waste is converting it into nutrient-rich compost. Through a natural process facilitated by bacteria, waste is decomposed and transformed into decayed organic matter known as humus or compost [35]. Compost is highly valuable for soil enrichment and is extensively used in organic farming [36]. During the decomposition process of organic waste by bacteria, the temperature can rise to 60 degrees Celsius or even higher. Consequently, this process takes time, which helps eliminate pathogens and prevents the production of harmful larvae. The result of this process is the production of healthy compost, which can be used to enrich the soil without any concerns. Composting waste is carried out through two methods: anaerobic or hot fermentation processes and mechanical composting. Food waste is recycled into compost in an environment with a high presence of oxygen. Fungi and bacteria break down the proteins, fats, and carbohydrates in the waste into compost and CO₂. Compost is a valuable resource that can aid in the better growth of fruits, vegetables, flowers, and even houseplants. It allows gardeners and farmers to use less water. Creating compost instead of sending food waste to landfills also has a significant impact on reducing global warming. When food waste decomposes in landfills, it produces methane, a greenhouse gas 72 times more potent than carbon dioxide [37, 38].

Compost Production Cycle for Animal Feed

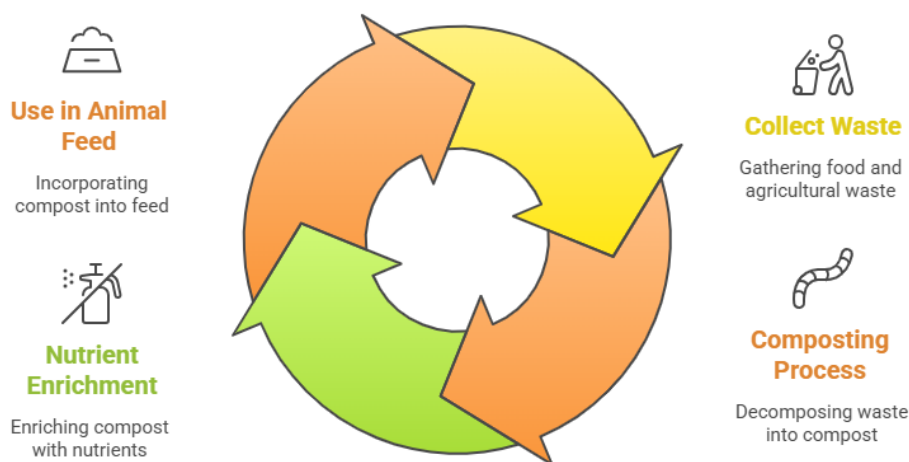


Figure 2. Compost production cycle for animal feed.

5.2. Food Waste as Biomass

Biomass is considered one of the key sources of renewable energy and refers to any living organism capable of growth and development, categorized based on natural laws. Biomass energy offers several advantages, including its ability to reduce greenhouse gas emissions when compared to fossil fuels, as it is considered carbon-neutral. This is because the carbon dioxide released during the combustion or decomposition of biomass is roughly equivalent to the amount absorbed by plants during their growth cycle. Additionally, biomass can utilize waste materials that would otherwise contribute to environmental pollution, promoting a more sustainable approach to waste management. Although biomass can serve as an energy source, it comes with problems too. The land and water needed for biomass production may conflict with food production, resulting in possible issues with food security. Moreover, uncontrolled biomass harvesting and processing can also result in deforestation, loss of wildlife habitat, and more. Therefore, the sustainable development of biomass energy requires careful planning, efficient technologies, and adherence to ecological principles. Technological advancements are continuously improving the efficiency of biomass energy conversion processes. For instance, modern methods such as anaerobic digestion, pyrolysis, and gasification allow for the production of high-quality biofuels and biogas with minimal environmental impact. Additionally, integrating biomass energy systems with other renewable energy sources, such as solar and wind, can enhance energy reliability and reduce dependency on non-renewable resources. As global energy demands increase, biomass is expected to play an increasingly important role in the transition to a more sustainable and low-carbon future. Governments, industries, and researchers are working collaboratively to address the challenges and maximize the potential of biomass as a key component of the renewable energy mix. With continued innovation and responsible practices, biomass energy has the potential to contribute significantly to global energy needs while supporting environmental and economic sustainability [39, 40].

5.3. Extracting Nutrients from Food Waste and Organic Materials

One method that shows great promise is the utilisation of food waste for the extraction of nutrients that can be used in hydroponic systems. By employing a compost based crop and hydroponic nutrients strategy, it can transform farming for the better. Research suggests that these organic options indeed boosted plant growth while reducing the dependency on nonrenewable inorganic salts used in traditional farming. Studies also note that biosolids together with the residue of vegetable crops have been shown to make powerful nutrient solutions that grow seedlings much better compared to traditional mineral fertilizers. This innovative strategy not

only addresses the urgent need for recycling organic waste but also plays a crucial role in enhancing food security by optimizing resource utilization and minimizing environmental impacts. As the agricultural sector seeks sustainable practices, the integration of nutrient extraction from food waste into hydroponic systems represents a significant advancement towards achieving a more resilient and eco-friendly food production framework [41, 42].

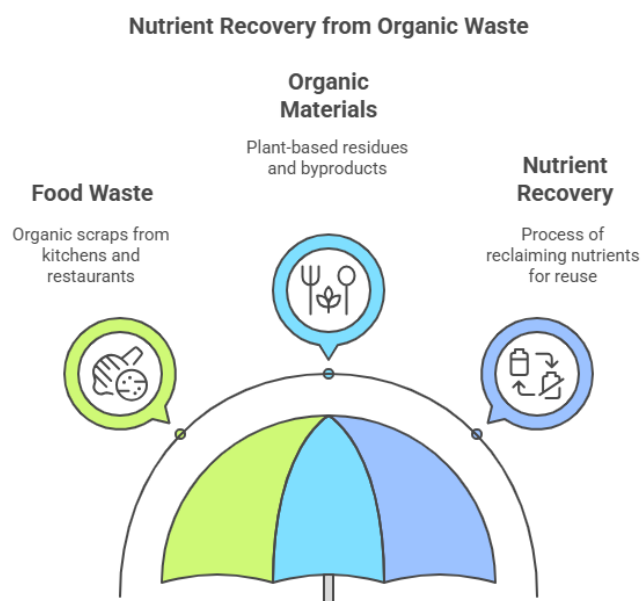


Figure 3. Nutrient Recovery Cycle from Organic Waste.

5.4. Microalgal Biomass and Food Waste as Raw Materials

The synthesis of chemicals is predominantly based on petroleum, which is expected to be depleted in the not-too-distant future. Consequently, research activities have focused on replacing petroleum with sustainable raw materials (e.g., biomass) for chemical synthesis. The growing interest in biomass as a feedstock for chemical production has led to increased cultivation of energy-rich non-food crops compared to food crops. This has also sparked a debate on whether the production of chemicals and energy should take precedence over food and feed production. One solution to the issue of agricultural land being occupied by non-food crops is the use of food waste streams, organic materials, and microalgal biomass. In fact, microalgae cultivated in bioreactors or open ponds do not compete with agricultural land. The carbohydrates, proteins, lipids, and fatty acids present in microalgal biomass are of significant importance, as these compounds can serve as raw materials for chemical production. So far, there has been limited public acceptance of products, especially food and dietary supplements, derived directly from food waste. Therefore, cultivating microalgae on food waste can be considered a hygienic step to transform

low-value waste into valuable raw materials, which can even be used as food and feed. Furthermore, the composition of microalgal biomass can be controlled by limiting specific nutrients such as carbohydrates, fats, polyunsaturated fatty acids, or protein content, leading to higher yields of the desired compounds [43, 44].

5.5. Production of Yeast Extract Powder from Agricultural and Food Waste

Production of yeast extract powder from agricultural and food waste involves an innovative approach to sustainable resource utilization. This process not only helps in managing waste effectively but also contributes to the creation of a high-value product widely used in food, pharmaceutical, and biotechnology industries. By utilizing by-products such as fruit peels, vegetable scraps, and other organic residues, the method reduces environmental impact while promoting circular economy principles. The production process typically includes several key steps. In the beginning, food waste is collected and treated to scrub away dirt. These complex molecules are subsequently broken down with the help of enzymatic hydrolysis to simpler compounds along with nutrients required for yeast growth. The fermentation stage follows, where yeast is cultured in the nutrient-rich medium derived from the waste. After sufficient growth, the yeast cells are harvested, autolyzed, and processed to extract the desired components. Finally, the extract is dried into a powder form for easy storage and application. This product converts into amino acids, which hold nutritional value for livestock, aquatic animals, and humans. It can be utilized as a source of nitrogen and vitamins, as well as a nutritional supplement in the culture medium of microorganisms. This approach not only addresses waste management challenges but also offers economic benefits by converting low-cost waste into a commercially valuable product. Further research and technological advancements can enhance efficiency, scalability, and the range of raw materials that can be utilized, making this method an integral part of sustainable industrial practices [45, 46].

5.6. Production of Cellulose Nanocrystals

The food industry generates substantial quantities of organic waste, including by-products from fruit and vegetable processing, dairy production, and meat processing, as well as wastewater rich in nutrients and organic matter. These waste streams, if not managed properly, can lead to significant environmental and health issues, including water contamination, greenhouse gas emissions, and odor problems. However, they also present an opportunity for resource recovery and sustainable development. One promising approach to managing these wastes is the production of value-added materials, such as bacterial cellulose, through microbial fermentation. Cellulose is one of the most abundant

natural polymers in the world. However, it can also be produced by certain microorganisms, such as various types of bacteria (including species like *Acetobacter*, *Agrobacterium*, *Gluconacetobacter*, *Rhizobium*, and *Sarcina*). The cellulose produced by these organisms has the unique characteristic of having fiber sizes approximately 100 times smaller than plant cellulose, consisting of cellulose fibers at the nanoscale. Various properties of these materials, such as their high water retention capacity (over 200 times their dry weight), significant elasticity, remarkable mechanical properties in both dry and wet states, biodegradability, and high biocompatibility, have garnered attention. By utilizing microorganisms capable of converting organic waste into high-value products, researchers aim to address both waste management challenges and the growing demand for sustainable materials. For instance, food waste and nutrient-rich wastewater can serve as low-cost feedstocks for the cultivation of cellulose-producing bacteria. This not only reduces the environmental burden of waste disposal but also offers an economically viable pathway for producing bacterial cellulose with desirable properties. Bacterial cellulose derived from food industry waste has shown potential applications in various fields, such as medical dressings, wound healing, tissue engineering, and even as a component in biodegradable packaging materials. Its high purity, superior mechanical strength, and tunable properties make it a versatile material for advanced applications. Furthermore, integrating such biotechnological solutions into waste management systems can contribute to a circular economy, where waste is transformed into valuable resources rather than being discarded [47, 48].

5.7. Biogas

Biogas is a renewable natural energy source that has significant impacts on nature and industries. This gas is produced from the decomposition of organic materials, including animal manure, food waste, and wastewater. Manure and waste generate biogas through anaerobic digestion (i.e., without the presence of oxygen). Approximately 50-70% of biogas is composed of methane, making it flammable. By combining methane, hydrogen, and carbon monoxide gases with oxygen, fuel is produced, as air contains 21% oxygen. The release of energy in biogas is used as fuel. Biogas is the most cost-effective renewable fuel utilized in many countries. It is employed for cooking, cooling and heating, electricity generation, methanol and steam production, waste management, and mechanical power generation. Biogas is a mixture of methane, carbon dioxide, and small amounts of other gases, including hydrogen sulfide, nitrogen, hydrogen, methyl mercaptan, and oxygen. This composition makes it an ideal option for generating renewable energy. One of the significant contributions of biogas to nature is reducing the greenhouse effect. Biogas plants control the greenhouse effect. Plants absorb biogas and use it as

greenhouse fuel, thereby reducing methane emissions. Additionally, biogas production minimizes the need for fossil fuels like oil and coal. Another critical advantage of biogas is the production of natural gas, which does not require energy during its production process. Moreover, the raw materials used to produce biogas are entirely renewable; manure, raw materials, and food waste are always available [49-51]. Advantages of Biogas: Energy production (including heat, light, electricity), Reduction in the volume of disposed waste, Decrease in disease-causing agents (flies, worm eggs), Conversion of organic waste into high-quality fertilizer, Protection of vegetation, soil, and water, Increased efficiency in livestock farming and agriculture.

5.8. Biochar Production

Biochar is derived from the combination of two words: "biomass," meaning biological mass, and "charcoal," meaning coal. This term entered the global scientific literature in the 20th century, although the use of this material dates back to before the discovery of the Americas (up to 500 years ago). Biochar, also referred to as biological charcoal, is a type of coal produced from plant biomass and agricultural waste, used primarily as a fertilizer. This substance is solid and rich in carbon, capable of storing it for thousands of years. Biochar contains carbon, hydrogen, oxygen, nitrogen, sulfur, and ash in varying amounts. The production of biochar is an effective way to manage waste. Burning and decomposing biological residues and organic compounds release significant amounts of carbon dioxide into the atmosphere. Biochar, being a stable and fixed form of carbon, can store large quantities of greenhouse gases for extended periods (centuries), thereby helping to control greenhouse gas levels. Scientific research has shown that applying a moderate amount of biochar can reduce nitrogen oxide (N_2O) emissions by up to 80% and methane emissions by up to 100%. Both gases are atmospheric pollutants and contributors to the greenhouse effect. Biochar can enable carbon sequestration in soil for thousands of years (carbon sequestration refers to the process of depositing and removing carbon from the atmosphere, essentially capturing excess carbon dioxide in the air through the aerial and underground parts of plants, plant residues, and algae to mitigate the adverse effects of global warming). Biochar can enhance fertilizer efficiency, reduce production costs, and decrease environmental pollution. It improves soil quality and increases its fertility. This type of fertilizer boosts agricultural yields and can protect plants against certain diseases. The long-term effectiveness and structural stability of soil due to biochar are among its key features. Biochar has the potential for nutrient recycling, soil aeration, economic benefits, waste management, and serving as a long-term, reliable method for carbon sequestration. Research indicates that applying biochar to plants requiring higher levels of potassium-based fertilizers and higher pH can improve performance. Other benefits of using biochar in agricultural

soils include increasing organic matter, enhancing water retention in soil, improving cation exchange capacity, interacting with soil nutrient cycles by moderating soil pH, reducing nutrient leaching, and decreasing irrigation and fertilizer needs. Its high specific surface area and functional group structure enable biochar to absorb and deactivate heavy metals in the soil. From a cultivation perspective, one advantage of biochar is managing agricultural waste. The expansion of organic farming on one hand and atmospheric pollution on the other have driven the increasing global use of this compound. The fertile Terra Preta soils in Brazil are a result of biochar application over more than a thousand years. Similarly, this technique (using partially burned agricultural residues) has been practiced in Japan and revived in recent years. Other countries are gradually becoming interested in this traditional yet effective method, making biochar a revitalized approach from ancient times for future agriculture [52-55].

5.9. Production of Single-Cell Proteins

The term "single-cell protein" refers to the dried cells of microorganisms such as bacteria, yeast, molds, algae, or fungi that are cultivated on a large scale and used as protein sources for animals or humans. In this context, both the extracted cellular protein and the entire cellular material may be referred to as SCP. The term SCP was first introduced by Professor Carl Wilson in 1944 at the Massachusetts Institute of Technology, USA. The first international conference on SCP was held in 1967 in Massachusetts, during which British Petroleum (BP) was recognized as the sole provider of industrial SCP production. Since then, numerous factories worldwide have engaged in the industrial production of SCP, primarily using two substrate sources: hydrocarbon-based and sugar-based substrates to feed microorganisms. Sugar-based substrates mainly include agricultural waste, wastewater from food industries, and the wood and paper industries, while hydrocarbon-based substrates primarily consist of petroleum derivatives, ethanol, and methanol. Producing protein from carbon-containing wastewater achieves two major objectives: reducing environmental pollution and producing a protein product that is affordable, of good quality, and highly nutritious. Studies indicate that most advancements in SCP production processes have been driven by oil companies. Consequently, developments in SCP production have coincided with fluctuations in oil prices, such that rising oil prices have significantly impacted the stagnation of the SCP industry. This correlation arises because 60 to 80 percent of the costs of an SCP production unit are related to raw material expenses. Additionally, the state of agriculture in various countries and access to inexpensive plant and animal protein sources also influence the interest in expanding SCP production units. This issue becomes particularly significant when transportation costs and the reduced quality of imported plant and animal protein sources over long distances and in

large volumes exceed the costs of biological production [56-60].

Advantages of Single-Cell Proteins

Single-cell proteins contain various amino acids, carbohydrates, fats, nucleic acids, mineral salts, and vitamins, offering a very high nutritional value. Using microorganisms to produce single-cell protein instead of relying on animal and plant protein sources has numerous advantages, presenting a promising outlook for the production of this type of protein. Some of these advantages include:

- 1) The possibility of genetically modifying microorganisms.
- 2) High growth rate and protein content of microorganisms.
- 3) Utilization of a wide range of methods, substrates, and microorganisms for production.
- 4) Independence of production from climatic changes.
- 5) Minimal space requirements for production and processing.
- 6) High production speed and efficiency due to the short cell division time of microorganisms.
- 7) Consistency in product quality throughout food processes.
- 8) Capability to produce microorganisms with high protein yields (based on dry weight). The protein content can constitute about 60% to 70% of the molecular weight [61].

5.10. Ethanol Production from Food and Agricultural Waste

The main wastes for ethanol production are fruits and vegetables. Most of the carbohydrates in the liquid and solid wastes of fruits and vegetables consist of soluble sugars and polysaccharides that are easily hydrolyzed. Solid wastes and wastewater from fruit and vegetable processing lines can be used for the fermentation of sugars. Apple pomace is one of the most important by-products of the apple cider vinegar and fruit juice processing industry and constitutes about 25% of the original fruit mass. Apple pomace mainly contains 4.66-2.78% moisture and 0.5-9.22% carbohydrates. Fermentable sugars in apple pomace, such as glucose, fructose, and sucrose, can be converted into ethanol. The ethanol production efficiency is 0.37-0.33 g of ethanol per g of glucose. During the processing of citrus fruits, about half of the fruit is used as juice, and the rest, including peel, core, etc., is used as waste. Cellulose, pectin, and hemicellulose in citrus peel waste can be converted by pectinase or cellulase enzymes into simple sugars that can be consumed by microorganisms to produce ethanol and other fermentation products [62, 63].

6. Fermentation of Food Processing Waste into Alcohol for Use in Vehicles

First-generation biofuels are made from sugars and vegetable oils found in food crops using standard processing technologies [64]. Second-generation biofuels are made from

a variety of feedstocks that require different technologies to extract useful energy. Second-generation feedstocks consist of lignocellulosic biomass, wood, agricultural waste, various wastes, and energy crops cultivated on marginal lands that cannot be used for food production. "Second-generation biofuels" is a term applied to emerging technologies that are destined for the conversion of these feedstocks to biofuels, and also to the application of non-food crops, biomass, and wastes as feedstocks in conventional biofuel processing technologies [65]. Second-generation biofuel technology was developed in response to food security concerns arising from the use of food crops to produce first-generation biofuels, allowing for the use of non-food biofuel feedstocks [66]. The diversion from food biomass to biofuel production can lead to competition for land used for food crops. First-generation bioethanol is produced by fermenting sugars from plants into ethanol, using a process similar to that used in brewing and winemaking. This requires the use of food and feed crops such as sugarcane, corn, wheat, and sugar beets. The concern is that if these food crops are used to produce biofuels, food prices could rise, and some countries could face shortages. Corn, wheat, and sugar beets can also require a lot of agricultural inputs in the form of fertilizer, which limits their ability to reduce greenhouse gases. Biodiesel produced by recycling canola oil, palm oil, or other vegetable oils is considered a first-generation biofuel. Second-generation biofuel processes aim to expand the range of biofuels that can be produced using biomass consisting of non-food residues from current crops, such as stalks, leaves, and bark left behind after the extraction of the food crop, as well as other crops that are not used for food purposes (non-food crops), such as grasses, legumes, jatropha, whole corn, miscanthus, and small grain cereals, as well as industrial waste such as wood chips, peels, and pulp from fruit pressing. The problem that second-generation biofuel processes address is the extraction of useful feedstocks from woody or fibrous biomass, where the useful sugars are locked up by lignin, hemicellulose, and cellulose. All plants contain lignin, hemicellulose, and cellulose, which are complex carbohydrates (sugar-based molecules). Cellulosic ethanol is made by breaking down cellulose sugar molecules using enzymes, steam heating, and other methods. These sugars can then be fermented to produce ethanol in the same way that first-generation bioethanol is produced. A byproduct of this process is lignin, which can be burned as a carbon-neutral fuel to generate heat and power for the processing plant and possibly for surrounding homes and businesses. Thermochemical processes in hydrothermal media can produce liquid oil products from a wide range of feedstocks that have the potential to replace or augment fuels. However, these liquid products do not meet the standards of diesel or biodiesel. Upgrading of the liquefaction products through one or more physical or chemical processes may improve their properties for use as fuels. Lim and Wang studied the microbial community for single-phase and two-phase anaerobic digestion of food waste and found a

dominance of Firmicutes and greater bacterial diversity in a two-phase continuous stirred tank reactor, resulting in 23% higher methane production compared to single-phase

anaerobic digestion. Methanosaeta dominated the archaeal community of the single-phase and two-phase reactors [67-69].

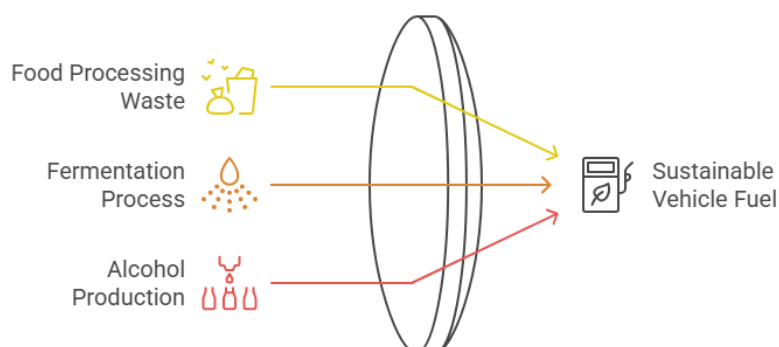


Figure 4. The cycle of converting food waste into sustainable vehicle fuel through the fermentation process.

7. Conclusion

The processing of food waste by microorganisms presents a promising solution to one of the most pressing environmental challenges of our time. By leveraging the natural abilities of these microorganisms, we can transform waste into valuable energy and products, fostering sustainability and resource efficiency. As research and technology continue to advance, the potential for microbial processing to play a pivotal role in waste management and energy production will only grow, paving the way for a more sustainable future.

Abbreviations

AD	Anaerobic Digestion
CO ₂	Carbon Dioxide
CH ₄	Methane
SDGs	Sustainable Development Goals
SCP	Single-Cell Protein
NGS	Next Generation Sequencing
PCR	Polymerase Chain Reaction
RFLP	Restriction Fragment Length Polymorphism
FAO	Food and Agriculture Organization
EM	Effective Microorganisms
GHG	Greenhouse Gas
DNA	Deoxyribonucleic Acid
RNA	Ribonucleic Acid
H ₂	Hydrogen
N ₂ O	Nitrous Oxide
C/N Ratio	Carbon-to-Nitrogen Ratio
pH	Potential of Hydrogen (Acidity/Alkalinity Index)
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand

CSTR	Continuous Stirred Tank Reactor
SCFA	Short-Chain Fatty Acids
SD	Standard Deviation
DM	Dry Matter

Author Contributions

Behzad Mohammadi is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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