

Zero-Waste Food Processing Technologies: Recent Advances, Vaporization Strategies, and Circular Bioeconomy Approaches

Rokalla Preethi

Department of Food Science and Technology
Punjab Agricultural University

Abstract

The global food industry generates vast amounts of food waste and by-products across processing, distribution, and consumption, leading to significant environmental, economic, and social challenges. Traditional linear food production is increasingly being replaced by zero-waste and circular bioeconomy strategies that prioritize resource efficiency, waste reduction, and the conversion of food residues into valuable products. Zero-waste food processing integrates sustainable methods, biorefinery concepts, renewable energy, biodegradable packaging, and smart waste management to maximize raw-material use and reduce environmental impact. Advances such as anaerobic digestion, microbial fermentation, thermochemical processing, green extraction, AI-assisted waste management, and biopolymer manufacturing have accelerated the shift toward sustainable food systems. This review explores emerging zero-waste technologies, pathways for food-waste valorization, industrial applications, environmental benefits, challenges, and future outlooks. Special attention is given to integrated biorefineries and circular-economy models that convert food waste into biofuels, bioactive compounds, biodegradable materials, fertilizers, and renewable energy. The review also discusses technological obstacles, economic constraints, and policy issues related to large-scale implementation. Zero-waste approaches are poised to play a key role in meeting sustainable development goals and building climate-resilient food systems.

Keywords: Zero-waste processing; Food waste valorization; Circular bioeconomy; Sustainable food systems; Biorefinery; Food waste management; Bio-based products

Graphical abstract



1. Introduction

The rapid growth of the global population, urbanization, industrialization, and changing dietary habits have significantly increased food production and consumption worldwide. Although advances in food processing technologies have improved food availability and shelf stability, enormous quantities of food waste and by-products are generated throughout the food supply chain. According to recent estimates, approximately one-third of all food produced for human consumption is lost or wasted annually, resulting in severe environmental, economic, and social consequences (Sharma, P et al 2021). Food waste is generated at multiple stages, including agricultural production, post-harvest handling, processing, storage, transportation, retail, and household consumption. The inefficient disposal of food waste through landfilling and incineration contributes substantially to greenhouse gas emissions, soil and water pollution, and depletion of valuable natural resources such as water, land, and energy.

Traditional food processing industries primarily follow a linear economic model based on the “take–make–dispose” principle, in which raw materials are processed into products and large amounts of waste are discarded without effective recovery or reuse. However, growing environmental concerns and the urgent need for sustainable resource management have accelerated the transition toward circular bioeconomy and zero-waste approaches in food systems. Zero-waste food processing technologies aim to minimize waste generation and maximize the use of food processing residues by recycling, reusing, recovering, and valorizing them into high-value products (Pal et al., 2024). These technologies promote sustainable production systems that integrate environmental protection, economic viability, and resource efficiency within closed-loop industrial frameworks.

Food processing residues are rich in carbohydrates, proteins, lipids, dietary fiber, minerals, and bioactive compounds, which can be converted into value-added products such as biofuels, biodegradable plastics, biofertilizers, enzymes, nutraceuticals, organic acids, and renewable chemicals. Recent advances in biorefinery concepts have demonstrated the potential of food waste as a key feedstock for sustainable industrial applications (Tsegaye et al., 2021). Integrated biorefinery systems use biological, chemical, and thermochemical technologies to achieve complete valorization of food residues while minimizing environmental burdens. These approaches significantly contribute to the transition from fossil-based economies toward sustainable circular bioeconomy systems.

Among zero-waste technologies, biological conversion methods such as anaerobic digestion, composting, microbial fermentation, and insect-based bioconversion have attracted substantial attention for their environmental compatibility and economic feasibility. Anaerobic digestion converts organic waste into biogas and nutrient-rich digestate through microbial degradation under oxygen-free conditions, thereby providing renewable energy and organic fertilizers. Similarly, microbial fermentation technologies enable the conversion of food waste into bioethanol, enzymes, probiotics, organic acids, and single-cell proteins, which have high industrial relevance (Ansari et al., 2024). In recent years, insect-mediated bioconversion using black soldier fly larvae has emerged as an efficient and sustainable method for converting food waste into protein-rich biomass for animal feed applications.

Thermochemical technologies, including pyrolysis, gasification, hydrothermal carbonization, and liquefaction, have also shown promise for sustainable food waste valorization. These technologies enable the production of biochar, syngas, bio-oil, and renewable fuels through controlled thermal degradation of organic residues. Biochar from food waste has attracted growing interest for use in soil improvement, carbon sequestration, wastewater treatment, and environmental remediation. Furthermore, integrated thermochemical-biological systems are being developed to improve energy efficiency and maximize resource recovery in circular food production systems (Singh et al., 2022).

In addition to energy recovery technologies, green extraction methods such as ultrasound-, microwave-, and enzyme-assisted extraction, as well as supercritical fluid extraction, are increasingly used to recover valuable bioactive compounds from food processing residues. Fruit peels, seeds, pomace, and cereal bran contain significant amounts of antioxidants, polyphenols, pigments, essential oils, and dietary fiber that can be used in the food, pharmaceutical, cosmetic, and packaging industries. Green extraction technologies offer several advantages, including reduced solvent use, lower energy requirements, shorter processing times, and improved extraction efficiency compared with conventional methods (Sharma, P et al., 2021).

Recent advances in artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), blockchain, and smart sensing technologies are further transforming waste management practices in the food processing industry. AI-

driven predictive models are increasingly used for process optimization, food quality monitoring, waste segregation, shelf-life prediction, and supply chain management. Smart technologies improve resource efficiency, reduce operational inefficiencies, and support data-driven decision-making in sustainable food systems. Moreover, AI-assisted life cycle assessment and digital monitoring systems significantly contribute to implementing circular bioeconomy frameworks in the food processing industry.

Despite significant technological advances, several challenges continue to impede the large-scale implementation of zero-waste food processing technologies. High capital investment, operational complexity, feedstock heterogeneity, regulatory barriers, and inadequate infrastructure remain major hurdles to industrial adoption. Furthermore, many emerging valorization technologies remain at the laboratory or pilot scale and require further optimization to achieve commercial feasibility (Cerdán et al., 2026). Therefore, multidisciplinary research integrating biotechnology, materials science, process engineering, and digital technologies is essential for developing economically viable and environmentally sustainable zero-waste food systems.

As global emphasis on sustainability, climate resilience, and circular-economy practices grows, zero-waste food-processing technologies are expected to play a vital role in future food systems. This review critically examines recent advances in biological, thermochemical, and green processing technologies for food-waste valorization. It also highlights circular bioeconomy strategies, AI-assisted waste management approaches, industrial applications, environmental benefits, challenges, and future perspectives associated with zero-waste food-processing technologies.

2. Food Waste Generation and Environmental Impacts

Food waste is generated at multiple stages of the food supply chain, including harvesting, post-harvest handling, processing, storage, transportation, retailing, and household consumption. Major food processing industries, such as fruit and vegetable processing, dairy, meat, seafood, cereal, and beverage, produce substantial quantities of organic residues rich in carbohydrates, proteins, lipids, dietary fiber, minerals, and bioactive compounds (Sharma, P et al., 2021; Zahid, A et al., 2022). Globally, approximately 1.3 billion tonnes of food are lost or wasted annually, representing nearly one-third of total food produced for human consumption (Gustavsson et al., 2019). Food processing residues, including fruit peels, pomace, whey, bran, husks, spent grains, and slaughterhouse wastes, are increasingly recognized as valuable feedstocks for sustainable biorefinery applications (Lin et al., 2013).

Improper disposal of food waste through landfilling and incineration causes severe environmental consequences, including methane emissions, leachate formation, groundwater contamination, and air pollution (Mirabella et al., 2014). Under anaerobic landfill conditions, decomposition of organic waste contributes substantially to greenhouse gas emissions and climate change because methane has a global warming potential significantly higher than that of carbon dioxide (Paritosh et al., 2017). Furthermore, food waste disposal results in considerable economic losses and inefficient use of agricultural resources, including land, fertilizers, water, labor, and energy (Ansari et al., 2024). The Food and Agriculture Organization (FAO) estimates that food waste accounts for approximately 8–10% of global greenhouse gas emissions annually, underscoring the urgent need for sustainable waste management strategies (Pal et al., 2024).

The environmental burden of food waste extends beyond greenhouse gas emissions to include biodiversity loss, excessive freshwater use, eutrophication, and soil degradation (Sharma, P et al., 2021). In addition, increasing urbanization and industrialization have intensified the generation of municipal organic waste, creating significant challenges for waste management infrastructure and landfill capacity. Conventional waste treatment methods are often energy-intensive and economically unsustainable, necessitating the development of innovative zero-waste technologies and circular bioeconomy frameworks (Tsegaye et al., 2021).

Transitioning to zero-waste food systems is essential for achieving the Sustainable Development Goals (SDGs), particularly those related to responsible production and consumption (SDG 12), climate action (SDG 13), affordable and clean energy (SDG 7), and sustainable industrial innovation (SDG 9). Circular economy approaches promote the recovery, recycling, and reuse of food processing residues as secondary raw materials for industrial applications, including biofuel production, biodegradable packaging, animal feed, organic fertilizers, and high-value bioactive compounds (Cerdán et al., 2026). Adopting sustainable food waste valorization technologies can significantly reduce environmental pollution while generating economic opportunities and enhancing resource efficiency in modern food systems.

3. Principles of Zero-Waste Food Processing

Zero-waste food processing is a sustainable industrial approach that aims to eliminate or substantially minimize waste throughout the food production chain by maximizing resource use, promoting recycling and reuse, and converting food residues into value-added products. Unlike conventional linear processing systems that follow the “take–make–dispose” model, zero-waste strategies are grounded in circular economy principles that promote the continuous use of resources within closed-loop systems (Sharma, P et al., 2021). The concept integrates environmental sustainability, economic efficiency, and technological innovation to achieve cleaner production and reduce the ecological footprint of food industries. Rapid industrialization and growing environmental concerns have intensified the need for sustainable food processing technologies that minimize resource depletion, greenhouse gas emissions, and waste accumulation (Pal et al., 2024). Zero-waste food processing systems rely on several interconnected principles, including waste prevention, resource recovery, integration of the circular bioeconomy, and sustainable energy use. These principles collectively support the development of environmentally sustainable food production systems while improving economic profitability and industrial efficiency.

3.1 Waste Prevention

Waste prevention is the primary and most effective principle of zero-waste food processing because it focuses on minimizing waste at the source before disposal or treatment is necessary. Waste prevention strategies include process optimization, precision manufacturing, efficient use of raw materials, improved supply chain management, and the adoption of smart technologies to reduce food losses during production, storage, transportation, and distribution (Mirabella et al., 2014). Implementing preventive measures significantly reduces environmental pollution, energy consumption, and operational costs associated with waste handling and disposal.

In the food processing industry, substantial quantities of waste are generated due to trimming losses, inefficient processing operations, product damage, improper storage conditions, and quality rejections during sorting and grading. Advanced manufacturing technologies such as automation, artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT)-based monitoring systems are increasingly being utilized to improve process efficiency and reduce material losses (Ansari et al., 2024). AI-assisted predictive analytics and sensor-based quality control systems help optimize processing conditions, monitor equipment performance, and predict shelf-life deterioration, thereby minimizing unnecessary product wastage.

Precision food processing technologies such as automated portioning, laser-guided cutting, robotic sorting, and smart packaging systems have demonstrated significant potential to reduce raw material losses and improve production efficiency. Furthermore, cold chain optimization and intelligent logistics management contribute substantially to minimizing post-harvest losses and spoilage during transportation and storage (Tsegaye et al., 2021). Consumer awareness programs and sustainable consumption practices also play important roles in waste prevention by encouraging responsible purchasing, storage, and food utilization behaviors. The adoption of lean manufacturing and cleaner production strategies has become increasingly important in modern food industries. Cleaner production focuses on reducing waste generation through energy-efficient technologies, process redesign, water conservation, and the reuse of processing materials. Such preventive approaches are economically advantageous because they reduce production costs while improving environmental sustainability and resource utilization efficiency (Sharma, P et al 2021).

3.2 Resource Recovery

Resource recovery is a fundamental component of zero-waste food processing, converting food processing residues and by-products into valuable secondary products. Food industry by-products are rich in carbohydrates, proteins, lipids, fiber, minerals, enzymes, and bioactive compounds that can be used across the food, pharmaceutical, agricultural, cosmetic, and bioenergy industries (Lin et al., 2013). Rather than disposing of these residues in landfills, resource recovery technologies enable their sustainable valorization into economically valuable materials. Several food processing industries generate large quantities of recoverable by-products. Fruit and vegetable processing industries produce peels, pomace, seeds, and pulp residues rich in polyphenols, antioxidants, pigments, and dietary fiber. Dairy industries generate whey containing lactose and proteins, while cereal industries produce bran and husks rich in fiber and bioactive compounds. Meat and seafood processing industries also generate protein-rich wastes suitable for enzyme production, animal feed, and collagen extraction (Zahid, A et al., 2022).

Biological, chemical, and thermochemical technologies are widely used to recover resources from food waste streams. Fermentation technologies convert organic residues into bioethanol, organic acids, enzymes, probiotics, and single-cell proteins. Anaerobic digestion produces biogas and nutrient-rich digestate from biodegradable waste, whereas thermochemical technologies such as pyrolysis and gasification yield biochar, syngas, and bio-oil (Singh et al., 2022). Green extraction technologies, including ultrasound-assisted, microwave-assisted, enzyme-assisted, and supercritical fluid extraction, are increasingly used to recover high-value bioactive compounds from food processing residues.

Recovered food waste components are also used to produce biodegradable packaging materials, edible coatings, biofertilizers, and functional food ingredients. For example, polysaccharides, proteins, and lipids extracted from food waste can be converted into biodegradable films and bioplastics, providing sustainable alternatives to petroleum-based plastics (Pal et al., 2024). These valorization strategies not only reduce environmental pollution but also generate additional revenue streams for the food industry. Resource recovery significantly contributes to sustainable resource management, reduced dependence on landfills, conservation of natural resources, and mitigation of greenhouse gas emissions. Therefore, efficient valorization technologies are essential for achieving circular food systems and improving industrial sustainability.

3.3 Circular Bioeconomy

The circular bioeconomy is an advanced sustainability framework that integrates renewable biological resources into circular production systems, in which waste materials are continuously reused, recycled, and transformed into new products. Unlike the conventional linear economy, which relies heavily on extraction and disposal, the circular bioeconomy emphasizes regenerative production models that minimize waste and maximize resource efficiency (Cerdán et al., 2026).

Food waste plays a central role in circular bioeconomy systems because it represents a renewable feedstock for producing bio-based chemicals, materials, fuels, fertilizers, and energy. Circular bioeconomy approaches promote cascading utilization of biomass, where food residues are sequentially processed into multiple high-value products before final energy recovery. This integrated approach enhances resource utilization efficiency and reduces environmental impacts (Pal et al., 2024). Biorefinery systems are considered the cornerstone of circular bioeconomy strategies in food industries. Biorefineries integrate biological, chemical, and thermochemical processes to convert food waste into multiple products including biofuels, bioplastics, organic acids, enzymes, nutraceuticals, and renewable chemicals. Integrated biorefineries enhance economic feasibility by maximizing product diversity and minimizing waste disposal requirements (Tsegaye et al., 2021).

Circular bioeconomy frameworks also support sustainable agriculture by recycling nutrients and producing organic fertilizers. Composting and anaerobic digestion convert organic residues into nutrient-rich fertilizers that improve soil fertility and reduce reliance on synthetic fertilizers. Furthermore, biodegradable materials derived from food waste contribute to sustainable packaging systems and help reduce plastic pollution. Implementing circular bioeconomy principles yields several environmental benefits, including reduced greenhouse gas emissions, conservation of fossil resources, less landfill accumulation, and improved ecosystem sustainability. Additionally, circular production systems create economic opportunities through the development of new industries, job creation, and enhanced industrial competitiveness. Governments and international organizations are increasingly promoting circular bioeconomy policies to achieve sustainable development goals and climate neutrality targets (Sharma, P et al., 2021).

3.4 Sustainable Energy Integration

Sustainable energy integration is essential for zero-waste food processing systems because food waste contains substantial biodegradable organic matter suitable for renewable energy production. Conventional energy sources based on fossil fuels contribute heavily to greenhouse gas emissions and environmental degradation. Therefore, integrating renewable energy recovery technologies into food processing industries can substantially improve sustainability and energy efficiency (Paritosh et al., 2017).

Anaerobic digestion is among the most widely adopted technologies for generating renewable energy from food waste. During anaerobic digestion, microorganisms degrade organic waste in the absence of oxygen to produce biogas containing methane and carbon dioxide. Biogas can be used for electricity generation, heating, cooking, and industrial

energy applications, while the digestate can be used as an organic fertilizer (Singh et al., 2022). Co-digestion of food waste with agricultural residues and sewage sludge has been shown to increase methane yield and improve process stability. Thermochemical conversion technologies such as pyrolysis, gasification, and hydrothermal carbonization are increasingly used to convert food waste into renewable fuels and energy-rich products. Pyrolysis converts organic residues into biochar, bio-oil, and syngas under oxygen-limited conditions, whereas gasification produces combustible syngas via partial oxidation at high temperatures. Hydrothermal carbonization is particularly effective for wet biomass because it eliminates the need for drying before processing (Ansari et al., 2024).

Biohydrogen production via dark fermentation and microbial electrolysis is another emerging sustainable energy technology attracting significant research attention. Hydrogen is considered a clean fuel because it produces water as the primary by-product during combustion. Integrating biohydrogen production with wastewater treatment and food waste valorization offers substantial opportunities for sustainable energy generation within circular bioeconomy systems. Sustainable energy integration also includes the use of solar energy, waste heat recovery systems, and energy-efficient processing technologies in the food industry. Smart energy management systems and AI-assisted process optimization further improve energy conservation and operational efficiency. Incorporating renewable energy technologies into zero-waste food processing systems significantly reduces the carbon footprint, enhances energy security, and advances long-term environmental sustainability.

4. Biological Technologies for Zero-Waste Food Processing

Biological technologies are pivotal to zero-waste food processing systems, enabling the environmentally sustainable conversion of organic food residues into renewable energy, biofertilizers, animal feed, bioactive compounds, and other value-added products. These technologies primarily rely on microorganisms and enzymes to degrade and transform biodegradable food waste under controlled conditions. Compared with conventional disposal methods such as landfilling and incineration, biological processes are more sustainable because they reduce greenhouse gas emissions, minimize environmental pollution, and facilitate nutrient recycling within circular bioeconomy systems (Sharma, P et al., 2021). Food waste from agricultural activities, food processing industries, restaurants, retail markets, and households contains large amounts of biodegradable organic matter rich in carbohydrates, proteins, lipids, minerals, and moisture. Such nutrient-rich substrates provide excellent feedstock for biological conversion technologies, including anaerobic digestion, composting, microbial fermentation, and insect-based bioconversion. Recent advances in biotechnology, microbial engineering, and systems optimization have significantly improved the efficiency and industrial applicability of these technologies (Ansari et al., 2024).

4.1 Anaerobic Digestion

Anaerobic digestion (AD) is a widely used and well-established biological technology for food waste valorization and renewable energy generation. In anaerobic digestion systems, complex organic materials are degraded by microbial consortia under oxygen-free conditions to produce biogas composed primarily of methane (CH_4) and carbon dioxide (CO_2) (Singh et al., 2022). The process also generates nutrient-rich digestate that can be used as a biofertilizer in agricultural applications, thereby supporting nutrient recycling and sustainable farming practices. Anaerobic digestion involves four major biochemical stages, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, complex polymers such as carbohydrates, proteins, and lipids are broken down into simpler compounds, including sugars, amino acids, and fatty acids. Acidogenic bacteria subsequently convert these products into volatile fatty acids, alcohols, hydrogen, and carbon dioxide. Acetogenic microorganisms further transform intermediate compounds into acetate and hydrogen, which methanogenic archaea finally convert into methane (Paritosh et al., 2017).

Food waste is an excellent substrate for anaerobic digestion because of its high organic content and biodegradability. However, mono-digestion of food waste can cause operational instability due to rapid acidification and nutrient imbalance. Therefore, co-digestion of food waste with agricultural residues, sewage sludge, or animal manure is increasingly practiced to improve process stability, methane yield, and nutrient balance (Singh et al., 2022). Co-digestion also enhances microbial diversity and reduces inhibitory effects from excessive lipid or protein degradation.

Recent technological advances, including thermophilic digestion, two-stage digesters, membrane bioreactors, and AI-assisted process monitoring, have significantly improved biogas productivity and operational efficiency. Pretreatment technologies such as thermal, ultrasonic, microwave, enzymatic, and alkaline methods are also used to enhance substrate

biodegradability and methane production efficiency (Sharma, P et al., 2021). Anaerobic digestion provides several environmental and economic benefits, including renewable energy generation, reduced landfill waste, greenhouse gas mitigation, odor reduction, and nutrient recovery. After purification, biogas generated during digestion can be used for electricity generation, industrial heating, cooking fuel, and transportation applications. Moreover, digestate serves as an eco-friendly alternative to synthetic fertilizers because it contains essential nutrients such as nitrogen, phosphorus, and potassium (Ansari et al., 2024). Consequently, anaerobic digestion is recognized as a key technology for sustainable waste management and circular bioeconomy implementation.

4.2 Composting and Vermicomposting

Composting is a biological process in which biodegradable organic waste is aerobically decomposed by microorganisms into stable, humus-like organic matter called compost. It is one of the oldest and most cost-effective waste management technologies for converting food waste into nutrient-rich organic fertilizer (Mirabella et al., 2014). The process involves the microbial degradation of organic matter under controlled conditions of temperature, moisture, aeration, and carbon-to-nitrogen ratio. During composting, bacteria, fungi, and actinomycetes degrade biodegradable materials through thermophilic and mesophilic phases, thereby stabilizing organic matter and eliminating pathogenic microorganisms. Properly matured compost improves soil fertility, enhances water retention, increases microbial activity, and promotes sustainable agricultural productivity (Zahid, A et al., 2022). Composting also reduces dependence on chemical fertilizers and minimizes the accumulation of organic waste in landfills.

Food processing residues, such as fruit and vegetable peels, coffee grounds, cereal bran, dairy waste, and agricultural residues, are commonly used as compost feedstocks due to their high organic content. Several composting systems, including windrow composting, in-vessel composting, aerated static piles, and rotary drum composting, are employed at industrial and municipal scales. Vermicomposting is an advanced biological waste management technology that uses earthworms, particularly *Eisenia fetida* and *Eudrilus eugeniae*, to accelerate decomposition and improve compost quality. Earthworms consume organic waste and convert it into nutrient-rich vermicast containing beneficial microorganisms, enzymes, plant growth hormones, and humic substances (Lim et al., 2016). Vermicompost has superior nutrient availability and microbial activity compared to conventional compost. Integrating composting and vermicomposting into zero-waste food processing systems significantly contributes to nutrient recycling, soil health improvement, and sustainable agriculture. Furthermore, these technologies reduce methane emissions associated with landfill disposal and support circular bioeconomy frameworks by transforming waste into valuable agricultural inputs.

4.3 Microbial Fermentation

Microbial fermentation is an environmentally sustainable biotechnology approach that uses microorganisms such as bacteria, fungi, and yeasts to convert food-waste substrates into high-value products, including enzymes, organic acids, probiotics, bioethanol, bioplastics, single-cell proteins, and bioactive compounds (Tsegaye et al., 2021). Fermentation-based valorization is gaining attention for its ability to efficiently utilize low-cost organic residues and generate commercially important products with minimal environmental impact.

Food waste contains abundant fermentable sugars, starches, proteins, and lipids, which serve as ideal substrates for microbial growth and metabolite production. Fruit pomace, whey, molasses, spent grains, bakery waste, and starch-rich residues are widely used in industrial fermentation. Depending on the desired product, fermentation may occur under aerobic or anaerobic conditions with specific microbial strains. Bioethanol production from food waste is among the most extensively studied fermentation applications. Sugary and starchy wastes are hydrolyzed into fermentable sugars and converted into ethanol by yeasts such as *Saccharomyces cerevisiae*. Bioethanol produced from food waste is a renewable alternative to fossil fuels and helps reduce greenhouse gas emissions (Paritosh et al., 2017).

Organic acids such as lactic acid, citric acid, succinic acid, and acetic acid are also produced through microbial fermentation of food processing residues. These organic acids are widely used in food preservation, pharmaceuticals, biodegradable plastics, and chemical industries. Additionally, Microbial fermentation enables the production of industrial enzymes, including proteases and amylases, cellulases, and lipases, that are extensively utilized in food processing operations (Ansari et al., 2024). Single-cell proteins (SCPs) produced from microbial biomass are emerging as sustainable protein sources for animal feed and human nutrition. Fermentation technologies also facilitate the production of probiotics and functional food ingredients with health-promoting properties.

Recent advances in metabolic engineering, synthetic biology, and systems biotechnology have substantially improved fermentation efficiency, substrate utilization, and product yields. Genetically engineered microorganisms with enhanced metabolic pathways are increasingly developed for large-scale industrial applications. Furthermore, integrated biorefinery systems that combine fermentation with downstream processing technologies are improving the economic feasibility and sustainability of microbial waste valorization.

4.4 Insect-Based Bioconversion

Insect-based bioconversion has emerged as a highly promising and sustainable biological technology for converting food waste into valuable protein-rich biomass and organic fertilizers. Among insect species, black soldier fly larvae (*Hermetia illucens*) have attracted significant attention for their exceptional ability to efficiently consume and convert diverse organic waste streams into nutrient-rich biomass (Razouk et al., 2024). Black soldier fly larvae can consume large quantities of food waste, including fruit and vegetable residues, kitchen waste, spent grains, dairy waste, and agricultural by-products. During feeding, larvae rapidly convert organic waste into proteins, lipids, and chitin-rich biomass suitable for animal and aquaculture feed, as well as biodiesel production. Residual frass generated during larval rearing can also be used as organic fertilizer, supporting nutrient recycling within circular bioeconomy systems.

Insect-based bioconversion offers several environmental advantages over conventional livestock production. Insects require significantly less land, water, feed, and energy while producing fewer greenhouse gas emissions (Razouk et al., 2024). Insect farming also has high feed conversion efficiency and rapid growth rates, making it economically attractive for sustainable protein production. Lipids extracted from insect biomass can be used for biodiesel and other industrial applications, while proteins and amino acids are valuable ingredients in poultry, fish, and pet feed. Chitin and chitosan extracted from insect exoskeletons also have considerable industrial importance in biomedical, pharmaceutical, and packaging applications.

Recent research has focused on optimizing larval growth conditions, substrate composition, and automated insect farming systems, as well as on safety regulations for insect-derived products. Artificial intelligence and IoT-based monitoring systems are increasingly integrated into insect farming operations to improve productivity and process control. Despite its promise, challenges such as regulatory approval, consumer acceptance, standardization, and pathogen control still limit the large-scale commercialization of insect-based bioconversion technologies. Nevertheless, rising global demand for sustainable protein sources and efficient organic waste management is expected to drive rapid growth in this sector in the coming years.

5. Thermochemical Conversion Technologies

Thermochemical conversion technologies are increasingly recognized as efficient and sustainable approaches for the valorization of food waste and other organic residues in zero-waste food processing systems. These technologies use heat, pressure, and controlled reaction environments to convert biomass into energy-rich products, including biofuels, biochar, and valuable chemicals. Compared with conventional biological treatment methods, thermochemical processes generally offer faster conversion rates, higher energy recovery efficiencies, and improved pathogen destruction (Paritosh et al., 2017). Furthermore, these technologies can process heterogeneous feedstocks and significantly reduce waste volume while generating commercially valuable products. Food waste from households, restaurants, food industries, agricultural activities, and municipal solid waste streams contains large amounts of carbon-rich organic materials suitable for thermochemical conversion. Technologies such as pyrolysis, gasification, hydrothermal carbonization, torrefaction, and liquefaction are widely studied for transforming food waste into renewable energy and bio-based materials (Ansari et al., 2024). Recent advancements in reactor design, catalytic processing, process integration, and AI-assisted optimization have further improved the industrial applicability and efficiency of these technologies.

5.1 Pyrolysis

Pyrolysis is a thermochemical process that thermally decomposes organic materials under oxygen-limited or oxygen-free conditions to produce biochar, bio-oil, and combustible gases collectively known as syngas (Singh et al., 2022). The process typically occurs at temperatures of 300°C to 700°C, depending on feedstock characteristics and the desired product composition. Pyrolysis is considered one of the most promising waste-to-energy technologies because it enables the simultaneous recovery of solid, liquid, and gaseous products from food waste. Pyrolysis can be classified into slow,

fast, and flash pyrolysis based on heating rate, residence time, and operating conditions. Slow pyrolysis primarily favors biochar production due to lower heating rates and longer residence times, whereas fast pyrolysis maximizes liquid bio-oil yield through rapid heating and shorter reaction times (Tripathi et al., 2016). Flash pyrolysis, characterized by extremely rapid heating, further enhances bio-oil production efficiency.

Biochar produced from food waste pyrolysis possesses a high carbon content, a porous structure, and a large surface area, making it highly suitable for soil amendment, carbon sequestration, heavy metal adsorption, and wastewater treatment applications. The incorporation of biochar into agricultural soils improves soil fertility, nutrient retention, water-holding capacity, and microbial activity while reducing greenhouse gas emissions (Sharma, P et al., 2021). Additionally, biochar contributes to long-term carbon storage, thereby supporting climate change mitigation strategies. Bio-oil generated during pyrolysis contains a complex mixture of hydrocarbons, phenols, aldehydes, ketones, and organic acids that can be upgraded into transportation fuels and industrial chemicals. Syngas produced during the process mainly consists of hydrogen, methane, carbon monoxide, and carbon dioxide, which can be utilized for electricity generation, industrial heating, and fuel synthesis (Paritosh et al., 2017).

Several factors, including feedstock composition, moisture content, temperature, heating rate, catalyst type, and reactor configuration, influence pyrolysis efficiency and product distribution. Recent Studies have focused on catalytic pyrolysis, microwave-assisted pyrolysis, and co-pyrolysis techniques to improve product quality and energy efficiency. Catalysts such as zeolites and metal oxides enhance bio-oil upgrading and reduce undesirable by-products (Ansari et al., 2024). Despite its considerable advantages, pyrolysis faces certain challenges, including high capital costs, feedstock variability, energy requirements, and complex product upgrading processes. Nevertheless, continuous technological advancements and increasing interest in renewable energy systems are expected to accelerate industrial adoption of pyrolysis technologies in sustainable waste management.

5.2 Gasification

Gasification is a high-temperature thermochemical conversion process in which carbonaceous materials are partially oxidized under limited oxygen or steam to produce synthesis gas (syngas), a combustible gaseous mixture primarily composed of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and carbon dioxide (CO_2) (Qian, J et al., 2026). Gasification typically operates at temperatures between $700^{\circ}C$ and $1200^{\circ}C$ and is widely considered an efficient waste-to-energy technology for converting food waste and biomass into renewable fuels and chemicals. The gasification process occurs through several sequential stages, including drying, pyrolysis, oxidation, and reduction. Initially, moisture is removed from the feedstock, followed by thermal decomposition into volatile compounds and char. Partial oxidation reactions generate the heat required to sustain the process, while reduction reactions produce syngas through interactions among char, steam, and carbon dioxide (Paritosh et al., 2017). Syngas generated from food waste gasification has multiple industrial applications, including electricity generation, industrial heating, hydrogen production, synthetic natural gas production, and Fischer-Tropsch fuel synthesis. Gasification systems integrated with gas turbines and internal combustion engines achieve higher energy conversion efficiencies and lower greenhouse gas emissions than conventional fossil fuel systems (Qian, J et al., 2026).

Several gasifier configurations including fixed-bed, fluidized-bed, entrained-flow, and plasma gasifiers are employed depending on feedstock characteristics and operational requirements. Fluidized-bed gasifiers are particularly preferred for food waste processing because they provide better heat transfer, uniform temperature distribution, and higher conversion efficiency. Gasification also offers significant environmental benefits by reducing landfill accumulation and minimizing methane emissions, and recovering energy from organic waste streams. Furthermore, ash and char residues generated during gasification can be utilized in construction materials and soil applications. However, tar formation, feedstock heterogeneity, high operational temperatures, and gas cleaning requirements remain major technical challenges associated with large-scale gasification systems (Ansari et al., 2024). Recent advancements in catalytic gasification, plasma-assisted gasification, and AI-based process optimization have improved syngas quality, energy efficiency, and operational stability. Hybrid gasification systems integrated with carbon capture technologies are also being explored for achieving carbon-neutral and negative-emission energy systems.

5.3 Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is an emerging thermochemical technology that converts wet biomass into carbon-rich hydrochar under subcritical water conditions at moderate temperatures (180–250°C) and elevated pressures (2–10 MPa) (Zhang et al., 2024). HTC is particularly advantageous for food waste processing because it can directly process high-moisture biomass without requiring energy-intensive drying operations. During HTC, organic materials undergo hydrolysis, dehydration, decarboxylation, and polymerization in hot compressed water, yielding hydrochar, aqueous by-products, and gaseous compounds. Hydrochar produced during HTC has high carbon content, hydrophobicity, and energy density, making it suitable for solid fuel applications, soil amendment, and adsorbent production (Sharma et al., 2021).

Food waste streams such as fruit peels, vegetable residues, sewage sludge, dairy waste, and kitchen waste are ideal feedstocks for HTC because of their high moisture content and biodegradability. Compared to pyrolysis and gasification, HTC operates at lower temperatures and produces fewer air pollutants, thereby improving environmental sustainability (Zhang, et al 2024). Hydrochar generated from food waste exhibits excellent adsorption properties for heavy metals and organic pollutants in wastewater treatment applications. Additionally, HTC-derived hydrochar can improve soil fertility, carbon sequestration, and microbial activity when applied as soil conditioner. The aqueous phase produced during HTC contains valuable nutrients and organic compounds that can be further utilized for anaerobic digestion and biochemical conversion processes.

Recent research has focused on catalyst-assisted HTC, co-hydrothermal carbonization, and process optimization to improve hydrochar yield, energy recovery, and nutrient recycling efficiency. Integration of HTC with biological treatment systems is also being explored to enhance overall waste valorization performance within circular bioeconomy frameworks. Despite its significant potential, HTC faces challenges such as reactor corrosion, process scalability, high-pressure operating requirements, and liquid by-product management. Nevertheless, HTC is increasingly recognized as a promising technology for the sustainable management of wet food waste streams.

5.4 Integrated Pyrolysis–Anaerobic Digestion Systems

Integrated thermochemical-biological systems that combine pyrolysis and anaerobic digestion have emerged as advanced, highly efficient approaches for comprehensive food waste valorization. These hybrid systems integrate the advantages of biological conversion and thermochemical processing to maximize energy recovery, nutrient recycling, carbon utilization, and waste reduction efficiency (Singh et al., 2022). In integrated pyrolysis–anaerobic digestion systems, biodegradable organic fractions of food waste are first subjected to anaerobic digestion to produce biogas. Residual digestate and solid residues from AD are then pyrolyzed to produce biochar, bio-oil, and syngas. This integration enhances overall resource recovery while minimizing residual waste disposal requirements. Biochar produced from digestate pyrolysis can be recycled back into anaerobic digesters to improve microbial activity, stabilize pH, adsorb inhibitory compounds, and enhance methane production efficiency (Qian, J et al., 2026). Biochar addition also improves nutrient retention and reduces ammonia inhibition during anaerobic digestion.

Integrated systems offer several environmental advantages, including reduced greenhouse gas emissions, improved carbon sequestration, enhanced nutrient recycling, and increased renewable energy production. Coupling pyrolysis with anaerobic digestion also reduces odor, pathogen contamination, and environmental pollution associated with conventional waste disposal methods (Singh et al., 2022). Recent studies have shown that integrated thermochemical-biological systems achieve higher overall energy conversion efficiencies than standalone technologies. Furthermore, combining biological and thermochemical processes enables more effective management of heterogeneous food waste streams and improves economic feasibility by generating multiple products. Advanced computational modeling, AI-assisted process monitoring, and life-cycle assessment studies are increasingly used to optimize integrated waste valorization systems. Future developments are expected to focus on scalable reactor designs, energy integration, catalyst development, and industrial implementation strategies for sustainable circular bioeconomy applications.

6. Green Extraction Technologies

Green extraction technologies have emerged as sustainable, environmentally friendly approaches for recovering valuable bioactive compounds from food processing residues and agricultural by-products. Conventional extraction methods

often require large volumes of organic solvents, prolonged extraction times, and high energy consumption, which can cause secondary pollution and reduce process sustainability. In contrast, green extraction technologies aim to minimize environmental impact by reducing solvent use, lowering energy requirements, improving extraction efficiency, and using eco-friendly processing conditions (Chemat et al., 2019).

Food processing waste, such as fruit peels, seeds, pomace, cereal bran, spent grains, and vegetable residues, is a rich source of polyphenols, antioxidants, pigments, essential oils, proteins, dietary fibers, vitamins, and other bioactive compounds. The recovery of these compounds through green extraction technologies supports zero-waste food processing systems by converting low-value waste materials into high-value functional ingredients for the food, pharmaceutical, nutraceutical, cosmetic, and packaging industries (Zahid, A. et al., 2022). Recent advancements in process engineering, biotechnology, nanotechnology, and sustainable chemistry have accelerated the development of several innovative green extraction methods, including ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, enzyme-assisted extraction, pulsed electric field extraction, and pressurized liquid extraction. These technologies contribute significantly to circular bioeconomy frameworks by enhancing resource utilization efficiency and reducing environmental burdens associated with food waste disposal (Sharma, P et al 2021).

6.1 Ultrasound-Assisted Extraction

Ultrasound-assisted extraction (UAE) is an advanced green extraction technique that uses ultrasonic waves, typically at 20-100 kHz, to enhance the release of bioactive compounds from plant and food matrices. The mechanism of UAE is primarily based on acoustic cavitation, in which the formation, growth, and collapse of microscopic bubbles generate intense localized pressure and temperature changes that disrupt cellular structures and improve mass transfer efficiency (Chemat et al., 2017). This cavitation effect ruptures plant cell walls, facilitating the release of intracellular compounds such as polyphenols, flavonoids, carotenoids, anthocyanins, essential oils, and antioxidants into the extraction solvent. Compared with conventional solvent extraction methods, UAE offers several advantages, including reduced extraction time, lower solvent consumption, improved extraction yield, reduced energy requirements, and preservation of thermolabile compounds (Rostagno et al., 2013).

Food processing residues such as citrus peels, grape pomace, mango peels, pomegranate husks, tomato waste, and cereal bran are commonly processed using UAE to recover valuable phytochemicals. UAE has proven highly effective at extracting phenolic compounds from fruit and vegetable wastes, owing to enhanced solvent penetration and improved disruption of lignocellulosic matrices (Zahid, A et al., 2022). Key process parameters, including ultrasound frequency, power intensity, extraction temperature, solvent composition, extraction time, and solid-to-liquid ratio, strongly influence extraction efficiency and product quality. Optimizing these parameters is essential to maximize bioactive recovery and minimize degradation of sensitive compounds. Recent studies have also explored integrating UAE with other extraction methods, such as microwave-assisted and enzyme-assisted extraction, to further improve extraction performance (Sharma, P et al., 2021). Industrial applications of UAE are rapidly expanding because of its scalability, economic feasibility, and compatibility with green processing principles. Additionally, UAE supports sustainable food processing by reducing waste generation and enabling efficient valorization of food residues into functional ingredients and natural additives.

6.2 Microwave-Assisted Extraction

Microwave-assisted extraction (MAE) is another highly efficient green extraction technology that uses microwave energy to rapidly heat solvents and biological materials, thereby enhancing extraction kinetics and mass transfer. Microwave radiation interacts with polar molecules and ions in the extraction medium, generating internal heating via dipole rotation and ionic conduction (Routray & Orsat, 2012). Unlike conventional heating methods that rely on heat conduction and convection, microwave heating heats the sample volumetrically, resulting in faster and more uniform heating. This rapid internal heating causes cell wall rupture, improved solvent penetration, and accelerated diffusion of bioactive compounds into the extraction solvent. Consequently, MAE significantly reduces extraction time, solvent consumption, and energy requirements while improving extraction efficiency (Chemat et al., 2019).

MAE is widely used to recover valuable phytochemicals, including polyphenols, flavonoids, carotenoids, pectins, anthocyanins, and essential oils, from food waste such as fruit peels, seeds, pomace, and agricultural residues. Citrus peels, apple pomace, grape seeds, and tomato skins are particularly suitable substrates for microwave-assisted recovery

of antioxidants and functional compounds (Zahid, A et al., 2022). Several factors, including microwave power, extraction time, solvent type, temperature, and moisture content, affect MAE efficiency and product quality. Optimizing processing conditions is essential to avoid thermal degradation of sensitive compounds and to maximize extraction yield. MAE has demonstrated excellent performance in recovering thermally stable phytochemicals, yielding higher purity and shorter processing times compared to conventional extraction methods (Routray & Orsat, 2012).

Recent technological developments include solvent-free microwave extraction, microwave hydro-diffusion, and hybrid microwave-ultrasound systems that further enhance sustainability and extraction performance. Industrial-scale MAE systems are increasingly adopted for the production of natural food additives, nutraceutical ingredients, and plant-based bioactives because of their operational efficiency and environmental advantages. The application of MAE in zero-waste food processing contributes significantly to sustainable waste valorization, circular economy implementation, and reduced chemical solvent use within food industries.

6.3 Supercritical Fluid Extraction

Supercritical fluid extraction (SFE) is an environmentally friendly extraction technology that uses supercritical fluids, particularly supercritical carbon dioxide (SC-CO₂), to recover oils, flavors, pigments, antioxidants, and nutraceutical compounds from food waste and plant materials. A supercritical fluid forms when a substance is maintained above its critical temperature and pressure, where it exhibits unique properties intermediate between liquids and gases (Herrero et al., 2010). Supercritical CO₂ is the most widely used extraction solvent because it is non-toxic, non-flammable, inexpensive, chemically inert, and easily removed from final products. Additionally, SC-CO₂ has excellent diffusivity and low viscosity, enabling efficient penetration into solid matrices and selective extraction of target compounds. The tunable solvating power of SC-CO₂ allows precise control over extraction selectivity by adjusting pressure and temperature (Chemat et al., 2019).

SFE is particularly effective for recovering lipophilic compounds such as essential oils, carotenoids, fatty acids, tocopherols, and flavor compounds from food processing residues. Coffee waste, citrus peels, grape seeds, tomato pomace, and spice residues are commonly used as feedstocks for SC-CO₂ extraction (Herrero et al., 2010). The absence of toxic organic solvents makes SFE highly suitable for food, pharmaceutical, and cosmetic applications requiring high-purity products. Compared with conventional solvent extraction methods, SFE offers numerous advantages, including solvent-free products, minimal thermal degradation, high selectivity, shorter extraction times, and environmentally sustainable processing conditions. Furthermore, carbon dioxide used during extraction can be recycled and reused, improving process sustainability and reducing environmental impact (Sharma, P et al., 2021). Recent research has focused on co-solvent-assisted SFE, nano-assisted extraction systems, and integrated extraction technologies to improve recovery of polar compounds and enhance extraction efficiency. Despite its advantages, large-scale industrial implementation of SFE is sometimes limited by high equipment costs and operational complexity. Nevertheless, increasing demand for natural and solvent-free products continues to drive adoption of SFE technologies in sustainable food processing industries.

6.4 Enzyme-Assisted Extraction

Enzyme-assisted extraction (EAE) is a green, biotechnology-based method that uses hydrolytic enzymes to degrade plant cell wall components, thereby facilitating the release of intracellular bioactive compounds. Enzymes such as cellulases, pectinases, hemicellulases, amylases, and proteases are commonly employed to hydrolyze complex polysaccharides and proteins in food waste matrices (Puri et al., 2012). Plant cell walls contain cellulose, hemicellulose, lignin, pectin, and other structural polymers that restrict solvent penetration and hinder extraction efficiency. Enzymatic treatments selectively break down these barriers, increasing permeability and improving the release of valuable compounds, including polyphenols, pigments, proteins, oils, dietary fibers, and antioxidants (Nadar et al., 2018). Food processing residues such as fruit peels, seeds, cereal bran, oilseed cakes, and vegetable waste are widely used in enzyme-assisted extraction processes. EAE has demonstrated remarkable efficiency in recovering pectin from citrus peels, phenolic compounds from grape pomace, proteins from oilseed residues, and antioxidants from fruit waste (Zahid, A et al., 2022).

Compared with conventional extraction techniques, EAE operates under mild processing conditions, reducing thermal degradation and preserving the bioactivity of sensitive compounds. Enzymatic extraction also reduces solvent use,

improves selectivity, and enhances product quality while minimizing environmental pollution (Puri et al., 2012). Several factors, including enzyme type, enzyme concentration, pH, temperature, substrate composition, and incubation time, significantly influence extraction efficiency. Optimizing these parameters is essential for achieving maximum recovery and ensuring process sustainability. Recent advances in immobilized enzymes, recombinant enzymes, and enzyme cocktail formulations have further improved industrial applicability and extraction performance. Integrating EAE with ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction has shown synergistic effects that enhance extraction efficiency and reduce processing time. Consequently, enzyme-assisted extraction is increasingly recognized as a promising sustainable technology for zero-waste food processing and circular bioeconomy applications. Green extraction technologies collectively contribute to sustainable food processing by enabling efficient recovery of valuable compounds from food waste streams while minimizing environmental impact. These technologies play a critical role in transforming food residues into functional ingredients, natural additives, biodegradable materials, and nutraceutical products, thereby supporting circular bioeconomy principles and zero-waste industrial systems.

7. Food Waste Valorization into Value-Added Products

Food waste valorization is the conversion of food processing residues and organic waste streams into economically valuable products using biological, chemical, and thermochemical technologies. Growing emphasis on sustainability, the circular bioeconomy, and resource efficiency has accelerated research into innovative valorization pathways that transform food waste into renewable fuels, biodegradable materials, functional ingredients, animal feed, fertilizers, and industrial chemicals (Sharma, P et al., 2021). Rather than disposing of food residues in landfills, modern zero-waste approaches focus on maximizing resource recovery and minimizing environmental impacts through integrated biorefinery systems. Food processing industries generate substantial quantities of by-products, including fruit peels, pomace, whey, spent grains, cereal bran, vegetable residues, oilseed cakes, and slaughterhouse waste. These materials contain abundant carbohydrates, proteins, lipids, fibers, minerals, and bioactive compounds that can serve as feedstocks for producing high-value products (Lin et al., 2013). Valorization technologies not only reduce waste accumulation and greenhouse gas emissions but also create new economic opportunities and improve industrial sustainability.

7.1 Biofuels

Biofuel production from food waste has emerged as a key waste valorization strategy to reduce dependence on fossil fuels and mitigate climate change. Food waste contains large amounts of biodegradable organic matter suitable for conversion into renewable fuels, including biodiesel, bioethanol, biomethane, biohydrogen, and syngas, via biochemical and thermochemical pathways (Paritosh et al., 2017). Bioethanol is commonly produced from carbohydrate-rich feedstocks, such as fruit residues, bakery waste, molasses, potato peels, and cereal by-products, through fermentation with microorganisms such as *Saccharomyces cerevisiae*. Starch and cellulose in food waste are hydrolyzed into fermentable sugars, which are then converted into ethanol. Bioethanol serves as a renewable transportation fuel and blending agent that reduces greenhouse gas emissions and fossil fuel consumption (Tsegaye et al., 2021).

Biodiesel production primarily utilizes lipid-rich food waste including waste cooking oil, animal fats, dairy residues, and oilseed processing waste. Biodiesel is produced through transesterification reactions involving triglycerides and short-chain alcohols in the presence of catalysts. Compared to conventional diesel fuel, biodiesel offers lower sulfur emissions, reduced particulate matter generation, and improved biodegradability (Ansari et al., 2024).

Biomethane production via anaerobic digestion is another widely adopted approach for converting organic food residues into renewable energy. During anaerobic digestion, microorganisms degrade organic matter under oxygen-free conditions to produce methane-rich biogas, which can be upgraded to biomethane for electricity generation, industrial heating, and transportation fuel (Singh et al., 2022). Biohydrogen production from food waste using dark fermentation, photo-fermentation, and microbial electrolysis is attracting growing research attention because hydrogen is considered a clean, high-energy fuel. Biohydrogen generation from food residues contributes significantly to sustainable energy systems and carbon-neutral fuel production (Paritosh et al., 2017).

Thermochemical technologies such as pyrolysis and gasification also enable the production of syngas and bio-oil from food waste. Syngas, which contains hydrogen and carbon monoxide, can be further used for fuel synthesis and electricity

generation. Integrated biorefinery systems that combine biological and thermochemical conversion technologies have demonstrated enhanced energy recovery efficiency and improved sustainability. Producing biofuels from food waste provides multiple environmental benefits, including reduced landfill disposal, greenhouse gas mitigation, renewable energy generation, and conservation of fossil resources. However, challenges such as feedstock variability, process optimization, and economic feasibility remain important considerations for large-scale commercialization.

7.2 Bioplastics and Biopolymers

The growing environmental concerns associated with petroleum-based plastics have accelerated the development of biodegradable bioplastics and bio-based polymers derived from renewable food waste. Food processing residues rich in starch, cellulose, hemicellulose, proteins, lipids, and other polysaccharides serve as sustainable feedstocks for producing biodegradable packaging materials and eco-friendly polymer systems (Nanda et al., 2022). Bioplastics produced from food waste are increasingly used in food packaging, agricultural films, biomedical applications, disposable utensils, and coating materials because of their biodegradability, renewability, and lower environmental footprint. Unlike conventional plastics, biodegradable polymers can decompose naturally through microbial activity, thereby reducing plastic pollution and landfill accumulation (Sharma, P et al 2021).

Polyhydroxyalkanoates (PHAs) are microbial biopolymers synthesized by bacteria under nutrient-limited conditions from organic substrates derived from food waste. PHAs are highly biodegradable, biocompatible, and thermoplastic, making them suitable alternatives to petroleum-based plastics. Food waste hydrolysates, whey, used cooking oils, and sugar-rich residues are commonly used for microbial PHA production (Koller et al., 2017). Polylactic acid (PLA) is another commercially important biodegradable polymer produced from lactic acid generated by microbial fermentation of starch-rich food residues. PLA exhibits good mechanical strength, transparency, and processability, making it widely used in food packaging and the biomedical industry. Agricultural and food processing wastes such as corn stover, potato waste, and fruit residues are increasingly explored as sustainable feedstocks for PLA production (Tsegaye et al., 2021). Starch-based films derived from potato peels, cassava waste, corn residues, and cereal by-products are extensively studied for biodegradable packaging applications. Natural polysaccharides such as cellulose, pectin, chitosan, and alginate, along with proteins extracted from food waste, also demonstrate excellent film-forming properties suitable for edible coatings and active packaging systems (Zahid, A et al., 2022).

Recent advances in nanotechnology, polymer blending, and active packaging have significantly improved the mechanical, barrier, antimicrobial, and antioxidant properties of bioplastics. Incorporating nanoparticles, essential oils, and natural antioxidants into biodegradable polymer matrices further enhances packaging performance and food preservation efficiency. Despite their considerable advantages, large-scale adoption of food waste-derived bioplastics faces challenges related to production costs, scalability, moisture sensitivity, and mechanical limitations. Nevertheless, increasing environmental regulations and consumer demand for sustainable packaging are expected to drive rapid growth in the biodegradable polymer industry.

7.3 Bioactive Compounds

Food processing residues are rich sources of valuable bioactive compounds, including antioxidants, polyphenols, flavonoids, carotenoids, anthocyanins, dietary fiber, vitamins, essential oils, and pigments. Recovering these compounds from food waste has become an important strategy for sustainable waste valorization and for developing functional ingredients for the food, pharmaceutical, cosmetic, and nutraceutical industries (Zahid, A et al., 2022). Fruit and vegetable wastes, such as citrus peels, grape pomace, mango peels, pomegranate husks, tomato skins, apple pomace, and berry residues, contain significant concentrations of phenolic compounds and antioxidants with strong antimicrobial, anti-inflammatory, anticancer, and cardioprotective properties (Chemat et al., 2019). These compounds are widely used in functional foods, dietary supplements, pharmaceuticals, and natural preservatives.

Dietary fibers recovered from cereal bran, fruit pomace, vegetable residues, and legume waste are increasingly used as functional food ingredients for their beneficial effects on gut health, cholesterol reduction, glycemic control, and obesity management. Pectin extracted from citrus and apple processing waste is widely used as a gelling and stabilizing agent in the food industry (Nanda et al., 2022). Natural pigments such as carotenoids, betalains, anthocyanins, and chlorophyll, extracted from food residues, are gaining considerable importance as alternatives to synthetic food colorants. Similarly,

essential oils recovered from citrus peels, herbs, and spice residues possess antioxidant and antimicrobial properties useful for food preservation and active packaging applications (Chemat et al., 2019).

Advanced green extraction technologies, including ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, and enzyme-assisted extraction, are increasingly used to efficiently recover bioactive compounds from food waste. These technologies improve extraction yields, reduce solvent consumption, preserve the bioactivity of sensitive compounds, and minimize environmental impact (Sharma, P et al., 2021). The use of food waste-derived bioactive compounds significantly contributes to the implementation of the circular bioeconomy, the reduction of synthetic additives, and the development of high-value functional products. However, challenges related to extraction efficiency, standardization, regulatory approval, and commercial scalability still require further research and technological advancements.

7.4 Animal Feed and Fertilizers

Food waste can be effectively processed into livestock feed and organic fertilizers, reducing resource waste and supporting sustainable agricultural systems. Converting food residues into feed and fertilizers is among the oldest and most economically viable waste valorization approaches within circular bioeconomy frameworks (Mirabella et al., 2014). Food processing by-products such as fruit pomace, brewery spent grains, oilseed cakes, whey, vegetable residues, bakery waste, and fish processing waste contain significant amounts of protein, carbohydrates, fiber, vitamins, and minerals suitable for animal nutrition. These materials can be processed through drying, fermentation, ensiling, or insect-based bioconversion to produce nutrient-rich feed ingredients for the poultry, aquaculture, cattle, and swine industries (Razouk et al., 2024).

Microbial fermentation and insect-based bioconversion technologies are increasingly used to improve the nutritional quality, digestibility, and safety of food waste-derived animal feeds. Black soldier fly larvae efficiently convert organic food waste into protein-rich biomass suitable for aquaculture and livestock feed, while simultaneously reducing organic waste volume (Razouk et al., 2024). Food waste-derived fertilizers are commonly produced through composting, vermicomposting, and anaerobic digestion. Compost and digestate generated from biodegradable food residues contain essential nutrients such as nitrogen, phosphorus, potassium, and organic matter, which improve soil fertility, microbial activity, and water retention capacity (Lim et al., 2016).

Organic fertilizers derived from food waste reduce reliance on synthetic fertilizers and support sustainable agriculture by improving soil health and nutrient recycling. Biofertilizers produced through microbial inoculation further enhance nutrient availability and promote plant growth. Using food waste for feed and fertilizer production yields substantial environmental benefits, including reduced landfill waste, mitigation of greenhouse gas emissions, nutrient recycling, and conservation of natural resources. However, proper treatment, quality control, pathogen management, and regulatory compliance are essential to ensure the safety and commercial acceptance of food waste-derived feed and fertilizer products.

Technology	Principle / Process	Major Applications	Advantages	Disadvantages / Limitations	Key References
Anaerobic Digestion (AD)	Microbial degradation of organic waste under anaerobic conditions to produce biogas and digestate	Biomethane production, renewable energy, organic fertilizer generation	Renewable energy generation; reduction of landfill waste; nutrient recycling; greenhouse gas mitigation; production of biofertilizer	Process instability due to feedstock variability; ammonia inhibition; high retention time; operational sensitivity to pH and temperature	Singh et al. (2022); Paritosh et al. (2017)

Technology	Principle / Process	Major Applications	Advantages	Disadvantages / Limitations	Key References
Composting	Aerobic microbial decomposition of biodegradable organic matter into stable compost	Organic fertilizer production, soil amendment	Simple and low-cost technology; improves soil fertility; reduces landfill accumulation; environmentally sustainable	Requires large land area; odor generation; long processing duration; nutrient losses during composting	Zahid, A et al (2022); Mirabella et al. (2014)
Vermicomposting	Biodegradation of food waste using earthworms and microorganisms	Production of nutrient-rich vermicompost and biofertilizer	Faster decomposition; enhanced nutrient quality; improved microbial activity; eco-friendly waste management	Sensitive to temperature and moisture; limited scalability; requires worm maintenance	Lim et al. (2016)
Microbial Fermentation	Conversion of food waste substrates into value-added products using microorganisms	Bioethanol, organic acids, enzymes, probiotics, single-cell proteins	High-value product generation; sustainable processing; low-cost substrates; reduced environmental pollution	Feedstock pretreatment required; contamination risks; downstream purification costs	Tsegaye et al. (2021); Ansari et al. (2024)
Insect-Based Bioconversion	Utilization of insects such as black soldier fly larvae to convert food waste into protein-rich biomass	Animal feed, biodiesel, organic fertilizers	High feed conversion efficiency; low environmental footprint; rapid waste reduction; sustainable protein production	Regulatory limitations; consumer acceptance issues; pathogen control challenges	Razouk et al. (2024)
Pyrolysis	Thermal decomposition of biomass under oxygen-free conditions	Biochar, bio-oil, syngas production	Multiple valuable products; carbon sequestration; waste volume reduction; renewable fuel production	High energy demand; expensive reactors; complex bio-oil upgrading; catalyst deactivation	Singh et al. (2022); Tripathi et al. (2016)

Technology	Principle / Process	Major Applications	Advantages	Disadvantages / Limitations	Key References
Gasification	Partial oxidation of organic materials at high temperatures to produce syngas	Electricity generation, fuel synthesis, industrial heating	High energy recovery efficiency; lower emissions than fossil fuels; flexible feedstock utilization	Tar formation; high operational temperatures; gas cleaning requirements; expensive infrastructure	Qian, J et al., 2026. Paritosh et al. (2017)
Hydrothermal Carbonization (HTC)	Conversion of wet biomass into hydrochar under subcritical water conditions	Hydrochar production, soil amendment, wastewater treatment	Suitable for wet biomass; no drying required; lower operating temperature than pyrolysis; improved carbon recovery	High-pressure operation; reactor corrosion; liquid waste management challenges	Zhang, et al 2024; Sharma, P et al (2021)
Integrated Pyrolysis–AD Systems	Combination of thermochemical and biological conversion technologies	Enhanced energy recovery, nutrient recycling, carbon utilization	Improved overall efficiency; multiple product recovery; reduced waste generation; better resource utilization	Complex integration; high capital cost; process optimization challenges	Singh et al. (2022)
Ultrasound-Assisted Extraction (UAE)	Cavitation-induced cell disruption using ultrasonic waves	Recovery of polyphenols, antioxidants, pigments, bioactives	Reduced extraction time; low solvent consumption; high extraction efficiency; preservation of thermolabile compounds	Equipment cost; scale-up challenges; possible degradation at high intensity	Chemat et al. (2017)
Microwave-Assisted Extraction (MAE)	Microwave energy enhances solvent penetration and extraction kinetics	Recovery of phytochemicals, pectin, antioxidants	Rapid extraction; lower solvent usage; energy-efficient; shorter processing time	Thermal degradation risk; uneven heating at large scale; high equipment cost	Routray & Orsat (2012); Chemat et al. (2019)
Supercritical Fluid Extraction (SFE)	Use of supercritical CO ₂ for solvent-free extraction of bioactives	Oils, flavors, nutraceuticals, pigments	Non-toxic solvent; high selectivity; solvent-free products;	High operational pressure; expensive equipment; limited	Herrero et al. (2010)

Technology	Principle Process	Major Applications	Advantages	Disadvantages / Limitations	Key References
			environmentally friendly	extraction of polar compounds	
Enzyme-Assisted Extraction (EAE)	Enzymatic hydrolysis of plant cell walls to release intracellular compounds	Recovery of phenolics, pectin, proteins, antioxidants	Mild processing conditions; improved extraction yield; reduced solvent use; eco-friendly	High enzyme cost; longer processing time; enzyme sensitivity to pH and temperature	Puri et al. (2012); Nadar et al. (2018)
Biofuel Production	Conversion of food waste into biodiesel, bioethanol, biomethane, and biohydrogen	Renewable transportation fuels and energy generation	Reduces fossil fuel dependence; greenhouse gas mitigation; energy recovery from waste	Feedstock inconsistency; high processing cost; purification requirements	Paritosh et al. (2017); Tsegaye et al. (2021)
Bioplastics and Biopolymers	Production of biodegradable polymers from food waste-derived biomolecules	Food packaging, biodegradable films, biomedical applications	Biodegradable; renewable resource utilization; reduced plastic pollution	Poor moisture resistance; lower mechanical strength; higher production cost	Koller et al. (2017); Nanda et al. (2022)
Bioactive Compound Recovery	Extraction of antioxidants, polyphenols, pigments, and dietary fibers from food residues	Nutraceuticals, pharmaceuticals, functional foods	High-value product generation; waste minimization; natural additive production	Extraction efficiency variability; purification challenges; storage stability issues	Zahid, A et al (2022); Chemat et al. (2019)
Animal Feed Production	Processing of food waste into nutrient-rich livestock and aquaculture feed	Poultry feed, fish feed, livestock feed	Reduces feed cost; nutrient recycling; sustainable agriculture support	Safety concerns; contamination risks; regulatory barriers	Razouk et al. (2024); Mirabella et al. (2014)
Organic Fertilizer Production	Conversion of food waste into compost, digestate, and biofertilizers	Soil fertility enhancement, sustainable agriculture	Improves soil health; reduces chemical fertilizer use; supports nutrient recycling	Transportation cost; odor issues; inconsistent nutrient composition	Lim et al. (2016); Paritosh et al. (2017)
AI-Assisted Waste Management	Application of AI and ML for predictive analytics and	Waste segregation, process control,	Improved operational efficiency; predictive monitoring;	High implementation cost; data dependency;	Benos et al. (2021); Kamble et al. (2020)

Technology	Principle Process	Major Applications	Advantages	Disadvantages / Limitations	Key References
	process optimization	inventory management	reduced waste generation; automation	cybersecurity concerns	
IoT and Smart Sensor Systems	Real-time monitoring using interconnected sensors and digital systems	Cold chain monitoring, shelf-life prediction, waste tracking	Real-time monitoring; improved traceability; reduced spoilage; enhanced logistics management	Infrastructure requirements; data privacy concerns; maintenance cost	Verdouw et al. (2016); Benos et al. (2021)
Blockchain Technology	Decentralized digital ledger for supply chain traceability	Food traceability, inventory management, food redistribution	Transparency; improved traceability; secure data management; reduced supply chain inefficiencies	Scalability limitations; energy consumption; integration complexity	Casino et al. (2019)
Robotic Waste Sorting Systems	AI-integrated robotics and image recognition for automated waste segregation	Recycling and food waste separation	High sorting accuracy; labor reduction; improved recycling efficiency; automation	High capital investment; maintenance complexity; technical expertise required	Kamble et al. (2020)

Table.1: Comparative Analysis of Zero-Waste Food Processing Technologies

8. Artificial Intelligence and Smart Technologies in Zero-Waste Processing

Artificial intelligence (AI), machine learning (ML), the Internet of Things (IoT), blockchain, robotics, big data analytics, and smart sensors are transforming modern food waste management and zero-waste systems. Incorporating digital technologies into food production, processing, storage, distribution, and waste recovery has greatly enhanced operational efficiency, resource utilization, traceability, and sustainability throughout food supply chains (Benos et al., 2021). These advanced technologies facilitate real-time monitoring, predictive analytics, automated decision-making, and process optimization, thereby advancing the circular bioeconomy and achieving sustainable development objectives.

Food waste generation is influenced by multiple factors, including inefficient processing operations, poor inventory management, inadequate storage conditions, inaccurate demand forecasting, and supply chain disruptions. Conventional waste management systems often have limited monitoring capabilities and delayed response mechanisms, leading to unnecessary food losses and environmental burdens. AI-driven systems provide advanced computational tools that analyze large datasets, predict waste-generation patterns, optimize process parameters, and improve overall resource-recovery efficiency (Sharma, P. et al., 2021). The adoption of Industry 4.0 technologies within the food industry has accelerated the development of intelligent and automated waste management systems. AI-assisted monitoring, cloud computing, edge computing, and cyber-physical systems are increasingly integrated into food processing operations to enhance productivity, reduce waste generation, and improve environmental sustainability.

8.1 Artificial Intelligence and Machine Learning in Waste Management

Artificial intelligence and machine learning technologies are widely used for predictive modeling, process optimization, demand forecasting, and decision support in food waste management. AI algorithms can analyze complex datasets generated from food processing operations, supply chains, consumer behavior, and environmental monitoring systems to identify inefficiencies and recommend corrective measures (Cillo et al., 2019).

Machine learning models, including artificial neural networks (ANNs), support vector machines (SVMs), random forests, and deep learning architectures, are increasingly used to predict food spoilage, shelf-life deterioration, inventory requirements, and waste-generation trends. Accurate prediction of food demand and consumption patterns enables industries and retailers to optimize production planning and inventory management, thereby minimizing overproduction and food losses (Benos et al., 2021). AI-assisted process optimization also improves the efficiency of biological and thermochemical waste valorization technologies, such as anaerobic digestion, fermentation, pyrolysis, and composting. Real-time monitoring systems integrated with AI algorithms can automatically adjust operational parameters, including temperature, pH, moisture content, aeration, and retention time, to maximize product yield and energy recovery efficiency (Sharma, P et al., 2021).

In waste segregation systems, AI-powered image recognition and computer vision enable automated identification and classification of food waste by composition, color, texture, and contamination level. Deep learning-based recognition systems significantly improve sorting accuracy and reduce human intervention in recycling and waste management facilities (Kamble et al., 2020). Recent advances in generative AI, reinforcement learning, and predictive analytics further enhance decision-making in sustainable food processing systems. AI-driven digital twins and simulation models also enable industries to evaluate waste management strategies and optimize circular bioeconomy frameworks before large-scale implementation.

8.2 Internet of Things (IoT) and Smart Sensor Technologies

The Internet of Things (IoT) comprises interconnected networks of sensors, devices, machines, and communication systems that collect, transmit, and analyze real-time data. IoT technologies are critical to modern zero-waste food processing systems, enabling continuous monitoring of food quality, storage and transportation conditions, and waste generation processes (Verdouw et al., 2016). Smart sensors integrated with IoT systems can monitor temperature, humidity, gas composition, pH, microbial growth, and storage conditions throughout food supply chains. This real-time monitoring helps prevent spoilage, maintain product quality, and extend shelf life, thereby significantly reducing food waste during storage and transportation (Benos et al., 2021).

IoT-enabled cold chain management systems are increasingly used across the dairy, meat, seafood, and fresh produce industries to ensure proper temperature control and minimize post-harvest losses. Wireless sensor networks and cloud-based monitoring platforms provide instant alerts when environmental conditions deviate, enabling rapid corrective actions and reducing spoilage risk. Smart bins and IoT-based waste monitoring systems are also being implemented in food industries, restaurants, supermarkets, and municipalities to enable efficient waste collection and segregation. These systems use weight sensors, fill-level detectors, RFID tags, and data analytics to optimize waste collection routes, improve recycling efficiency, and reduce operational costs (Kamble et al., 2020). Furthermore, IoT technologies enable the integration of food processing operations with AI-based predictive systems, enabling automated process control and energy-efficient waste valorization. Smart manufacturing systems that incorporate IoT and automation significantly improve productivity, resource utilization efficiency, and sustainability within zero-waste food processing industries.

8.3 Blockchain Technology and Supply Chain Traceability

Blockchain technology is emerging as a powerful digital solution to improve transparency, traceability, accountability, and trust in food supply chains. Blockchain is a decentralized and tamper-resistant digital ledger system that securely records and verifies transactions across multiple stakeholders in real time (Casino et al., 2019). Food waste often occurs because of poor traceability, inaccurate inventory management, counterfeit products, delayed transportation, and inefficient communication among supply chain participants. Blockchain technology enhances supply chain visibility by enabling secure tracking of food products from farm to consumer. This improved traceability helps identify critical points of food loss and enables rapid corrective interventions (Kamble et al., 2020).

Blockchain systems integrated with IoT sensors and QR codes provide real-time information regarding product origin, storage conditions, transportation history, processing details, and shelf-life status. Consumers, retailers, and manufacturers can access transparent product information, thereby improving food safety, quality assurance, and inventory management efficiency. Smart contracts powered by blockchain technology automate supply chain transactions and reduce administrative inefficiencies. Automated verification systems minimize delays and improve coordination among suppliers, distributors, retailers, and waste management facilities. Blockchain-based food redistribution systems also facilitate efficient donation of surplus food to charities and food banks, reducing edible food wastage (Casino et al., 2019). Recent developments in blockchain-enabled circular economy platforms support efficient tracking and valorization of food processing residues for biofuel production, composting, recycling, and biopolymer manufacturing. Although blockchain implementation faces challenges related to scalability, energy consumption, data privacy, and infrastructure costs, its integration with AI and IoT technologies offers substantial potential for sustainable and transparent food systems.

8.4 Robotics and Automated Waste Sorting Systems

Robotics and automated sorting technologies are transforming food waste segregation and recycling operations by improving sorting accuracy, operational efficiency, and labor productivity. Conventional manual sorting methods are often time-consuming, labor-intensive, inconsistent, and prone to contamination errors. AI-assisted robotic systems equipped with computer vision, sensors, and machine learning algorithms provide automated solutions for efficient waste separation and material recovery (Kamble et al., 2020).

Robotic waste sorting systems utilize advanced image recognition technologies, hyperspectral imaging, infrared sensors, and deep learning algorithms to identify and classify different waste components including plastics, metals, organic matter, paper, and glass. AI-powered robotic arms can rapidly separate recyclable materials and organic food waste with high precision, thereby improving recycling rates and reducing contamination levels. In food processing industries, robotic systems are increasingly employed for automated handling, sorting, packaging, and quality inspection of raw materials and food products. Such automation minimizes processing losses, improves operational consistency, and enhances food safety standards (Benos et al., 2021).

Recent advancements in collaborative robotics (cobots), autonomous mobile robots, and AI-based adaptive control systems have further improved flexibility and efficiency of waste management operations. Smart robotic systems integrated with cloud computing and IoT networks can continuously learn from operational data and optimize sorting performance over time. Automated waste-sorting systems also contribute significantly to the implementation of the circular bioeconomy by enabling efficient separation of organic fractions suitable for composting, anaerobic digestion, fermentation, and biofuel production. Moreover, robotics reduce occupational hazards associated with manual waste handling and improve hygiene within waste processing facilities. Despite their considerable advantages, adoption of AI-driven robotics and smart technologies in food waste management faces challenges including high initial investment costs, infrastructure requirements, cybersecurity concerns, and need for skilled workforce training. Nevertheless, ongoing advances in digital technologies and the growing emphasis on sustainability are expected to accelerate the adoption of intelligent zero-waste processing systems worldwide.

9. Circular Bioeconomy and Sustainable Development

The circular bioeconomy has emerged as a transformative sustainability framework aimed at replacing the traditional linear “take–make–dispose” economic model with regenerative systems that emphasize resource efficiency, waste minimization, recycling, and continuous utilization of renewable biological resources. In the context of food systems, circular bioeconomy approaches focus on converting food waste and agricultural residues into valuable products such as biofuels, bioplastics, biofertilizers, animal feed, renewable chemicals, and functional biomaterials (Sharma, P et al 2021). This approach not only reduces environmental pollution and landfill dependency but also creates economic opportunities through sustainable industrial development.

Food processing industries generate enormous quantities of biodegradable residues including fruit peels, pomace, whey, spent grains, cereal bran, oilseed cakes, and slaughterhouse by-products. Traditionally, these residues were disposed through landfilling or incineration, causing greenhouse gas emissions, nutrient losses, and environmental degradation. Circular bioeconomy systems instead consider these waste streams as renewable feedstocks for industrial applications

and resource recovery processes (Tsegaye et al., 2021). Consequently, food waste valorization has become a central pillar of sustainable food processing and zero-waste industrial systems.

9.1 Principles of Circular Bioeconomy in Food Systems

Circular bioeconomy frameworks are based on the principles of reducing resource consumption, reusing materials, recycling waste streams, and recovering value from biological residues. Unlike conventional linear systems, circular models promote cascading utilization of biomass, where food residues are sequentially processed into multiple value-added products before final energy recovery (Pal et al., 2024). In food industries, circular strategies include waste prevention, by-product valorization, nutrient recycling, renewable energy generation, sustainable packaging, and water reuse systems. These strategies enhance resource efficiency while reducing greenhouse gas emissions, environmental pollution, and dependence on non-renewable fossil resources (Lin et al., 2013).

The implementation of circular food systems requires integration of advanced technologies including anaerobic digestion, fermentation, pyrolysis, hydrothermal carbonization, green extraction technologies, and biopolymer production systems. These technologies enable comprehensive utilization of food waste streams while generating high-value products for food, pharmaceutical, agricultural, cosmetic, and energy sectors (Sharma, P et al 2021). Circular bioeconomy approaches also encourage industrial symbiosis, where waste generated by one industry serves as raw material for another industrial process. For example, food processing residues can be utilized as substrates for microbial fermentation, insect farming, composting, or biofuel production, thereby creating interconnected and resource-efficient industrial ecosystems.

9.2 Integrated Biorefinery Systems

Integrated biorefinery systems are considered the cornerstone of circular bioeconomy implementation because they enable comprehensive and efficient conversion of food waste into multiple valuable products through combined biological, chemical, and thermochemical processes. Similar to petroleum refineries that convert crude oil into diverse products, biorefineries utilize renewable biomass as feedstock for simultaneous production of fuels, chemicals, biomaterials, fertilizers, and energy (Tsegaye et al., 2021).

Food waste biorefineries integrate technologies such as anaerobic digestion, microbial fermentation, pyrolysis, gasification, hydrothermal carbonization, and green extraction methods to maximize resource recovery and minimize residual waste generation. For instance, carbohydrate-rich food waste can first undergo fermentation for bioethanol production, while residual solids are subsequently processed through anaerobic digestion for biomethane generation and pyrolysis for biochar production (Singh et al., 2022). Integrated systems provide several advantages over standalone technologies, including higher energy efficiency, improved economic feasibility, enhanced product diversity, and better environmental performance. Nutrient-rich digestate generated from anaerobic digestion can be recycled as organic fertilizer, whereas biochar produced through pyrolysis can be utilized for soil amendment and carbon sequestration (Paritosh et al., 2017).

Biorefineries also facilitate recovery of bioactive compounds, enzymes, proteins, pigments, dietary fibers, and biopolymers from food residues, thereby improving overall profitability and sustainability of food waste valorization systems. Advanced computational modeling, process integration, and AI-assisted optimization are increasingly being employed to improve operational efficiency and scalability of integrated biorefineries (Ansari et al., 2024). Furthermore, decentralized biorefinery systems are gaining attention for localized food waste management and renewable energy production in rural and urban communities. Such systems contribute to regional economic development, employment generation, and sustainable industrialization.

9.3 Environmental and Socioeconomic Benefits

The adoption of circular bioeconomy strategies in food processing industries offers significant environmental benefits by reducing landfill accumulation, greenhouse gas emissions, water pollution, and fossil fuel consumption. Organic waste decomposition in landfills generates methane, a potent greenhouse gas with substantially higher global warming potential than carbon dioxide. By diverting food waste toward valorization pathways such as anaerobic digestion and composting, circular systems significantly mitigate climate change impacts (Paritosh et al., 2017). Renewable energy

production from food waste through biomethane, biohydrogen, biodiesel, and bioethanol generation contributes to energy security and reduces dependence on fossil fuels. Additionally, biochar and organic fertilizers produced from food residues improve soil fertility, nutrient retention, and agricultural productivity while reducing reliance on synthetic agrochemicals (Pal et al., 2024).

Circular bioeconomy systems also promote conservation of natural resources including water, land, minerals, and energy through efficient recycling and reuse practices. Recovery of valuable biomolecules and functional compounds from food waste further reduces pressure on primary agricultural production systems. From a socioeconomic perspective, food waste valorization industries create new employment opportunities in waste collection, recycling, biotechnology, renewable energy, sustainable packaging, and bioprocess engineering sectors. Development of circular industrial ecosystems stimulates innovation, entrepreneurship, and investment in green technologies (Sharma, P et al 2021). Moreover, circular food systems improve food security by reducing post-harvest losses and maximizing utilization of agricultural resources. Redistribution of surplus edible food and conversion of unavoidable food waste into animal feed and fertilizers contribute to sustainable agricultural systems and resource-efficient food production.

9.4 Circular Bioeconomy and Sustainable Development Goals (SDGs)

The transition toward circular bioeconomy and zero-waste food systems strongly aligns with several United Nations Sustainable Development Goals (SDGs), particularly those focused on food security, clean energy, sustainable production, and climate action (United Nations, 2015).

SDG 2: Zero Hunger

Food waste reduction and resource-efficient food systems contribute significantly to SDG 2 by improving food availability, reducing post-harvest losses, and enhancing sustainable agricultural productivity. Valorization of food residues into animal feed, fertilizers, and functional ingredients helps optimize utilization of agricultural resources and supports global food security initiatives (Tsegaye et al., 2021).

SDG 7: Affordable and Clean Energy

Conversion of food waste into renewable energy sources such as biomethane, bioethanol, biodiesel, syngas, and biohydrogen directly supports SDG 7 by promoting access to affordable and sustainable energy systems. Renewable energy generation from food residues reduces fossil fuel dependency and contributes to low-carbon energy transitions (Paritosh et al., 2017).

SDG 12: Responsible Consumption and Production

Circular food systems are closely linked to SDG 12 because they encourage sustainable production practices, waste prevention, recycling, and efficient resource utilization. Adoption of green technologies, biodegradable packaging, smart supply chain management, and food waste valorization significantly reduces environmental impacts associated with food production and consumption (Sharma, P et al 2021).

SDG 13: Climate Action

Food waste valorization technologies contribute substantially to climate change mitigation by reducing methane emissions from landfills, promoting carbon sequestration through biochar application, and replacing fossil fuels with renewable bioenergy. Circular bioeconomy frameworks therefore play a critical role in achieving global carbon neutrality and climate resilience goals (Pal et al., 2024).

In addition to these goals, circular bioeconomy approaches also support SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), and SDG 15 (Life on Land). Consequently, the integration of circular bioeconomy principles into food processing industries is considered essential for achieving long-term environmental sustainability and sustainable global development.

10. Challenges and Future Perspectives

Despite considerable technological progress, several barriers hinder the large-scale implementation of zero-waste food processing technologies. High initial investment costs, operational expenses, and technological complexity limit

industrial adoption. Heterogeneous composition and seasonal variation of food waste affect process efficiency and product quality. scale-up challenges, energy consumption, and low conversion efficiencies remain significant concerns for several emerging technologies. The lack of standardized regulations and policy frameworks for food waste valorization hinders commercialization. Future research should focus on integrated biorefinery systems, AI-assisted process optimization, low-energy technologies, and scalable industrial applications. The development of multidisciplinary approaches that combine biotechnology, materials science, and digital technologies will accelerate the transition toward sustainable, zero-waste food systems.

Conclusion

Zero-waste food processing technologies represent a transformative approach for sustainable food production and waste management. Emerging biological, thermochemical, and green extraction technologies enable efficient conversion of food residues into renewable energy, bioactive compounds, biodegradable materials, and high-value products. Integration of circular bioeconomy principles with advanced digital technologies such as AI and IoT further enhances resource efficiency and environmental sustainability. Although challenges related to scalability, economics, and regulation remain, continuous technological innovation and supportive policy frameworks are expected to drive widespread adoption of zero-waste food systems. Future food industries will increasingly rely on integrated biorefinery concepts and circular production models to achieve sustainability goals and climate resilience.

References

1. Ansari, S. A., Kumar, T., Sawarkar, R., Gobade, M., Khan, D., & Singh, L. (2024). Valorization of food waste: A comprehensive review of individual technologies for producing bio-based products. *Journal of Environmental Management*, 364, 121439.
2. Arvelli, S., Jia, L., Zhang, M., & Zhao, J. (2025). Review of advanced technologies and circular pathways for food waste valorization. *Journal of Agricultural and Food Chemistry*, 73(26), 16085-16108.
3. Sharma, P., Gaur, V. K., Sirohi, R., Varjani, S., Kim, S. H., & Wong, J. W. (2021). Sustainable processing of food waste for production of bio-based products for circular bioeconomy. *Bioresource Technology*, 325, 124684.
4. Benos, L., Bechar, A., & Bochtis, D. (2020). Safety and ergonomics in human-robot interactive agricultural operations. *Biosystems Engineering*, 200, 55-72.
5. Casino, F., Dasaklis, T. K., & Patsakis, C. (2019). A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics and informatics*, 36, 55-81.
6. Cerdán, J. M. A., Kodama, T. K., Oliveira, G. H. D., Fuess, L. T., Andrade, J. F. C., & Ometto, A. R. (2026). Conversion of municipal biowaste into value-added products toward a circular bioeconomy: bridging the gap between laboratory-scale and full-scale implementation. *Clean Technologies and Environmental Policy*, 28(4), 89.
7. Chemat, F., Rombaut, N., Sicaire, A. G., Meullemiestre, A., Fabiano-Tixier, A. S., & Abert-Vian, M. (2017). Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review. *Ultrasonics sonochemistry*, 34, 540-560.
8. Chemat, F., Vian, M. A., & Cravotto, G. (2012). Green extraction of natural products: Concept and principles. *International journal of molecular sciences*, 13(7), 8615-8627.
9. Cillo, V., Petruzzelli, A. M., Ardito, L., & Del Giudice, M. (2019). Understanding sustainable innovation: A systematic literature review. *Corporate social responsibility and environmental management*, 26(5), 1012-1025.
10. Dey, S., Talukdar, A., & Bhattacharya, S. (2025). Microbial degradation and valorization of food wastes: waste to wealth approaches towards sustainability. *Discover Chemistry*, 2(1), 147.
11. Meybeck, A., Cederberg, C., Gustavsson, J., van Otterdijk, R., & Sonesson, U. (2011). Global food losses and food waste.
12. Herrero, M., Cifuentes, A., & Ibañez, E. (2006). Sub-and supercritical fluid extraction of functional ingredients from different natural sources: Plants, food-by-products, algae and microalgae: A review. *Food chemistry*, 98(1), 136-148.
13. Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2020). Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications. *International journal of production economics*, 219, 179-194.

14. Gaur, P., Kumari, K., Sharma, P., Gupta, V., & Gaur, V. K. (2025). Biological Processes for Food Waste Treatment. In *Sustainable Technologies for Food Waste Management* (pp. 49-67). CRC Press.
15. Koller, M., Maršálek, L., de Sousa Dias, M. M., & Braunegg, G. (2017). Producing microbial polyhydroxyalkanoate (PHA) biopolyesters in a sustainable manner. *New biotechnology*, 37, 24-38.
16. Lim, S. L., Lee, L. H., & Wu, T. Y. (2016). Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: recent overview, greenhouse gases emissions and economic analysis. *Journal of cleaner production*, 111, 262-278.
17. Lin, C. S. K., Pfaltzgraff, L. A., Herrero-Davila, L., Mubofu, E. B., Abderrahim, S., Clark, J. H., ... & Luque, R. (2013). Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. *Energy & Environmental Science*, 6(2), 426-464.
18. Zhang, X., Wang, Z., Yan, B., Li, J., Cui, X., & Chen, G. Integration of Anaerobic Digestion and Hydrothermal Carbonization for P-Enriched Hydrochar Production and Nutrients Recovery. *Available at SSRN 5039566*.
19. Mirabella, N., Castellani, V., & Sala, S. (2014). Current options for the valorization of food manufacturing waste: a review. *Journal of cleaner production*, 65, 28-41.
20. Qian, J., Jiang, S., Lv, B., & Zheng, X. (2026). Thermochemical Conversion of Food Waste into Biochar/Hydrochar for Soil Amendment: A Review. *Agronomy*.
21. Nadar, S. S., Rao, P., & Rathod, V. K. (2018). Enzyme assisted extraction of biomolecules as an approach to novel extraction technology: A review. *Food Research International*, 108, 309-330.
22. Nanda, S., Patra, B. R., Patel, R., Bakos, J., & Dalai, A. K. (2022). Innovations in applications and prospects of bioplastics and biopolymers: a review. *Environmental Chemistry Letters*, 20(1), 379-395.
23. Pal, P., Singh, A. K., Srivastava, R. K., Rathore, S. S., Sahoo, U. K., Subudhi, S., ... & Prus, P. (2024). Circular bioeconomy in action: Transforming food wastes into renewable food resources. *Foods*, 13(18), 3007.
24. Paritosh, K., Kushwaha, S. K., Yadav, M., Pareek, N., Chawade, A., & Vivekanand, V. (2017). Food waste to energy: an overview of sustainable approaches for food waste management and nutrient recycling. *BioMed research international*, 2017(1), 2370927.
25. Puri, M., Sharma, D., & Barrow, C. J. (2012). Enzyme-assisted extraction of bioactives from plants. *Trends in biotechnology*, 30(1), 37-44.
26. Razouk, A., Tiganescu, E., Von Glahn, A. J., Abdin, A. Y., Nasim, M. J., & Jacob, C. (2024). The future in the litter bin—bioconversion of food waste as driver of a circular bioeconomy. *Frontiers in Nutrition*, 11, 1325190.
27. Prado, J. M., & Rostagno, M. A. (Eds.). (2022). *Natural product extraction: principles and applications* (Vol. 71). Royal Society of Chemistry.
28. Routray, W., & Orsat, V. (2012). Microwave-assisted extraction of flavonoids: a review. *Food and Bioprocess Technology*, 5(2), 409-424.
29. Zahid, A., & Khedkar, R. (2022). Valorisation of fruit & vegetable wastes: a review. *Current Nutrition & Food Science*, 18(3), 315-328.
30. Singh, R., Paritosh, K., Pareek, N., & Vivekanand, V. (2022). Integrated system of anaerobic digestion and pyrolysis for valorization of agricultural and food waste towards circular bioeconomy. *Bioresource technology*, 360, 127596.
31. Sivalingam, S., Nandhitha, S., & Pragadheeshwaran, S. T. (2026). A comprehensive review on cradle to cradle strategies for sustainable food waste valorization. *Discover Food*.
32. Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and sustainable energy reviews*, 55, 467-481.
33. Tsegaye, B., Jaiswal, S., & Jaiswal, A. K. (2021). Food waste biorefinery: pathway towards circular bioeconomy. *Foods*, 10(6), 1174.
34. Assembly, U. G. (2015). Transforming our world: the 2030 Agenda for Sustainable Development.
35. Verdouw, C. N., Wolfert, J., Beulens, A. J. M., & Rialland, A. (2016). Virtualization of food supply chains with the internet of things. *Journal of Food Engineering*, 176, 128-136.