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Review

Food Waste to Food Security: Transition from Bioresources to Sustainability

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Abstract: The transition from food waste to food security is a critical component of sustainability efforts. This approach focuses on repurposing organic waste products generated throughout the food supply chain into valuable resources. Food waste, encompassing everything from agricultural residues to post-consumer waste, represents a significant untapped potential that can be harnessed to enhance food security. By implementing strategies such as composting, bioconversion, and innovative recycling technologies, biowastes can be transformed into fertilizers, animal feed, and even new food products, thus closing the loop in the food system and aiding sustainable solutions for waste valorization. This transition not only addresses environmental concerns by reducing landfill waste and greenhouse gas emissions but also contributes to economic sustainability by creating new opportunities within the food production and waste management sectors. Ultimately, transforming food waste into a resource aligns with the broader goals of a circular economy, ensuring a sustainable, resilient, and food-secure future.

Keywords: valorization; food waste; bioresources; sustainability; food security

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1. Introduction

The global food system produces enough food to feed every person on the planet, yet millions of people remain hungry. According to recent estimates by the Food and Agriculture Organization (FAO), around 828 million people experience food insecurity, while 1.3 billion tonnes of food, approximately one-third of all food produced globally, is wasted each year [1]. This paradox not only underscores inefficiencies in the global food supply chain but also emphasizes the need to address food waste as a critical component of food security efforts. Food waste occurs at various stages of the supply chain, including agricultural production, post-harvest handling, processing, distribution, and household consumption (see Figure 1). In developing countries, food waste is often due to inadequate infrastructure, such as poor storage facilities and transportation networks, which lead to spoilage [2]. Conversely, in developed nations, waste at the retail and consumer levels is a significant problem, often driven by cosmetic standards for food, over-purchasing, and improper storage. In the United States alone, nearly 40% of food produced is never consumed, while over 34 million people face food insecurity [3]. Similarly, in Europe, the European Commission estimates that around 88 million tonnes of food are wasted annually, costing the European economy over €143 billion [4]. This widespread wastage of food translates into lost opportunities to feed vulnerable populations and creates additional pressure on the environment through wasted resources such as water, land, and energy.

This juxtaposition of food waste and food insecurity highlights a pressing challenge: if food waste could be significantly reduced or repurposed, it could contribute to alleviating hunger and improving food security globally. Repurposing even a fraction of the wasted food could address the dietary needs of millions of people. For instance, it has been estimated that recovering just one-quarter of all wasted food could feed 870 million people, effectively ending global hunger [5]. The concept of sustainability is rooted in reducing the consumption of finite resources, minimizing waste, and closing material loops, creating a circular system where waste becomes a resource. In this context, food waste management plays a pivotal role in promoting environmental sustainability, economic resilience, and food security. By transforming biowastes, organic wastes derived from agricultural, food processing, and consumer activities, into valuable bioresources, we can address multiple challenges simultaneously. Table 1 summarizes various food waste valorization technologies, highlighting their environmental, economic, and social impacts as well as the types of bioproducts generated.

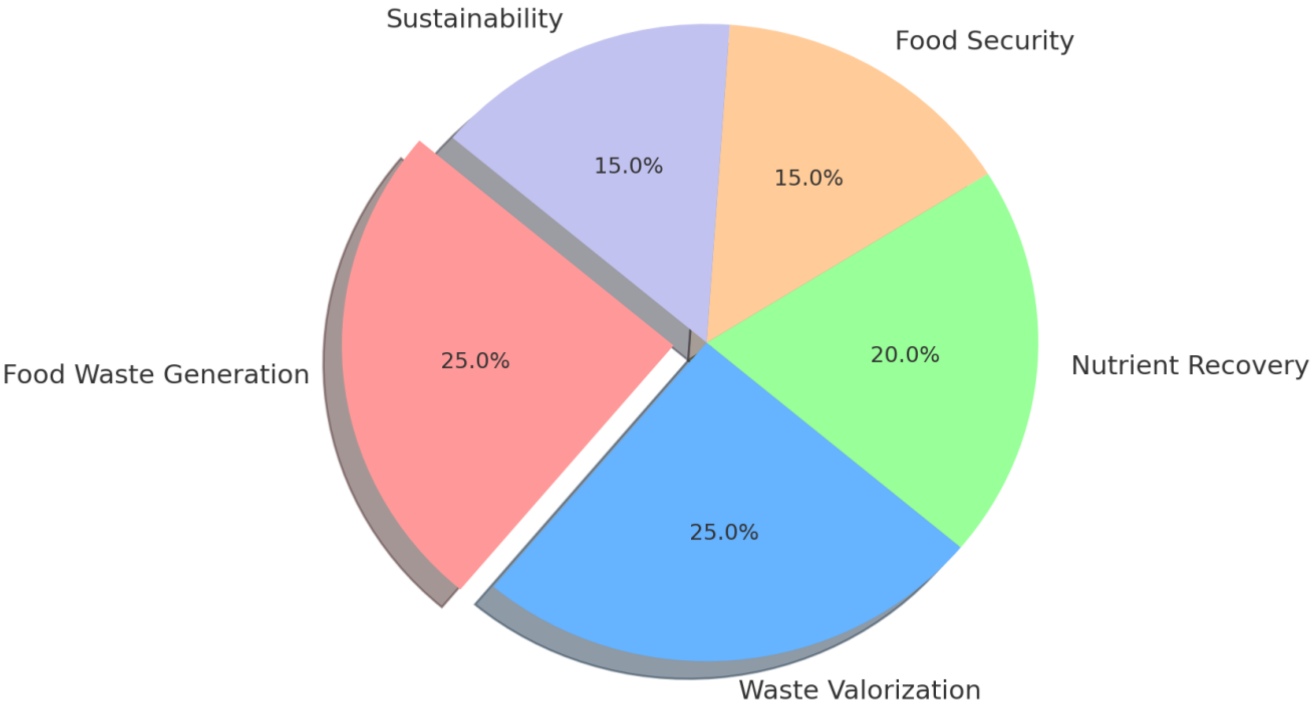

Figure 1. Transition from food waste to food security, highlighting the key components such as food waste generation, waste valorization, nutrient recovery, food security, and sustainability.

One of the primary environmental concerns related to food waste is the production of methane, a potent greenhouse gas, when organic waste decomposes in landfills. Food waste accounts for 8–10% of total global greenhouse gas emissions, meaning it significantly contributes to climate change [6]. Valorizing food waste, such as converting it into biofuels, compost, or animal feed, can reduce these emissions while providing new resources for agriculture and energy production. In the Netherlands, an innovative food waste-to-energy initiative converts organic food waste into biogas, which is then used to power homes and businesses [7]. This reduces reliance on fossil fuels and closes the loop in the energy system by turning waste into a sustainable energy source. Similarly, composting food waste can enrich soils, reduce the need for chemical fertilizers, and enhance agricultural productivity, creating a more sustainable agricultural cycle [8]. From an economic perspective, addressing food waste offers opportunities for new industries and job creation. In South Korea, a mandatory food waste recycling program has led to the development of a robust industry that repurposes food waste into biofertilizers and animal feed [9]. This initiative not only reduces waste but also generates revenue, improves agricultural productivity, and reduces the country's dependency on imported fertilizers. Furthermore, addressing food waste contributes to achieving key United Nations Sustainable Development Goals (SDGs). SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production) both emphasize the importance of reducing food loss and waste [5–10]. By tackling food waste, nations can reduce the strain on natural resources, create more resilient food systems, and ensure that food is distributed more equitably. Repurposing food waste into new resources, whether through composting, bioconversion, or innovative recycling technologies, creates a closed-loop system that not only addresses food security but also enhances environmental sustainability [11]. Moving forward, the integration of food waste management into national sustainability strategies will be essential to building a more resilient and sustainable global food system. The transition from food waste to bioresources plays a critical role in achieving food security and sustainability. By adopting biowaste conversion technologies such as composting, anaerobic digestion, and upcycling, food waste can be redirected from landfills and transformed into valuable products that enhance agricultural productivity and promote environmental health. This review will explore the various technologies, strategies, and policy frameworks that support the shift from food waste to sustainability and food security.

Table 1. Comparative analysis of food waste valorization technologies.

Technology	Type of Waste Treated	Primary Outputs	Environmental Benefits	Economic Impact	Social Impact
Anaerobic Digestion	Organic food waste, agricultural residues	Biogas, digestate	Reduces GHG emissions by 1000 kg CO_2 equivalent/tonne of waste	Generates biogas for energy production; saves energy costs	Supports local energy needs, creates jobs in rural areas
Composting	Organic food waste	Compost, soil conditioner	Reduces landfill waste; lowers methane emissions	Lowers cost of chemical fertilizers	Enhances soil health; supports local agriculture
Upcycling	Edible food waste (e.g., fruit peels)	Value-added food products	Reduces waste by repurposing 20–30% of food waste	Generates revenue from new food products	Creates new market opportunities
Biofertilizer Production	Organic food waste, kitchen scraps	Biofertilizers	Reduces reliance on chemical fertilizers	Saves on imported fertilizer costs	Improves food security; increases farmer income
Biofuel Production	Oils, fats, and certain organic wastes	Biodiesel, ethanol	Reduces dependency on fossil fuels	Generates renewable energy, cuts energy import costs	Contributes to energy security, creates green jobs
Animal Feed Production	Non-toxic, edible food waste	Animal feed	Prevents methane from decomposing in landfills	Reduces feed costs in livestock industry	Supports livestock farming; promotes circular economy

This manuscript stands out for its comprehensive and integrative approach to food waste valorization, emphasizing its potential to enhance food security and contribute to a sustainable, circular bioeconomy. Unlike other reviews or research papers that may focus on isolated aspects of food waste management, this manuscript provides a multi-dimensional analysis of how various technologies and strategies can address environmental, economic, and social challenges simultaneously. A key differentiator is the emphasis on food security as a core outcome. Many studies discuss food waste valorization in terms of environmental and economic benefits, but this manuscript specifically highlights food security as a critical goal. It explores how repurposing food waste can directly and indirectly reduce hunger by transforming biowastes into resources that support agricultural productivity, generate alternative food sources, and relieve pressure on food systems. The manuscript aligns food waste valorization with circular bioeconomy principles, offering a holistic perspective that underscores the interconnectedness of sustainability, food security, and waste management. By reframing food waste as a valuable resource within a closed-loop system, it demonstrates how bioconversion technologies can promote environmental resilience, economic sustainability, and social equity. It also includes a systematic comparison of various food waste valorization technologies, such as composting, anaerobic digestion, bioconversion, and upcycling. Through a structured evaluation of these methods, it assesses their contributions to environmental sustainability, resource efficiency, and economic resilience. Tables and figures synthesize recent data on conversion efficiencies, product yields, and environmental impacts, providing readers with a clear, quantitative overview of current innovations and trends.

Further distinguishing the manuscript is its focus on policy and alignment with the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production). This policy-oriented approach underscores the broader importance of food waste management in meeting international sustainability objectives, setting this review apart from others that may not address the policy implications of food waste valorization. The manuscript also includes recent, real-world examples, such as South Korea's food waste recycling program, the Netherlands' food-to-energy initiative, and Insectta's black soldier fly (BSF) bioconversion practices. These case studies showcase the practical viability of food waste valorization on a global scale, demonstrating scalable solutions that connect research with application. Beyond summarizing existing technologies, the manuscript identifies gaps in current research and suggests areas for future innovation. It advocates for exploring new bioconversion techniques and policy frameworks that can enhance the efficiency and scalability of food waste valorization, promoting long-term food security and sustainability. In essence, this manuscript uniquely contributes by framing food waste valorization as a pathway to achieving food security within a sustainable, circular bioeconomy. Through its integrative approach, it bridges environmental sustainability, economic development, and food security, making it a valuable resource for stakeholders looking to tackle food waste with innovative, multi-dimensional solutions.

2. Methods for Collection of Data and Information

To comprehensively examine the topic of food waste valorization and its potential for resource recovery, an extensive search was conducted across major research databases, including PubMed, Scopus, Web of Science, and ScienceDirect. The search focused on studies published within the last five years, capturing recent advancements alongside historical perspectives in food waste valorization. A targeted search strategy was applied using specific keywords such as "food waste valorization", "by-product utilization", "sustainability", "bioresource recovery", and "food industry waste management". Articles were selected based on relevance and quality, prioritizing studies detailing processes that convert food waste into valuable resources like energy, biochemicals, or biofuels, with an emphasis on their role in enhancing food security. Only peer-reviewed articles in English that provided experimental data on valorization techniques were included. Exclusion criteria filtered out review articles, studies lacking empirical data, and those focused solely on waste management without valorization. Relevant data were systematically extracted from the selected studies and organized into tables for review purposes. Key information gathered included the types of food waste utilized, valorization processes (such as fermentation, extraction, and pyrolysis), products generated, process efficiencies, and any reported benefits or challenges. The data were then categorized by valorization technique and outcomes, enabling identification of trends and innovations in food waste applications. Quantitative data, including yields and conversion efficiencies, were summarized to provide insights into technological performance. Tables and figures were created to visually represent methods, findings, and potential applications of each valorization approach. This structured and transparent methodology supports a comprehensive review of food waste valorization techniques, resource recovery, and their role in promoting sustainable food systems, thereby contributing to the transition towards sustainability in food security.

3. The Scope of Food Waste

Food waste is a multifaceted problem that affects every stage of the supply chain, from initial agricultural production to consumer-level waste. The issue is not merely about lost food but also about the significant resources that are wasted along with it, such as water, energy, labor, and land [12]. Figure 2 demonstrates the extent and impact of food waste across various stages of the supply chain. Understanding the various sources of food waste is essential to developing solutions that can address these inefficiencies and ultimately improve both food security and environmental sustainability. At the agricultural production level, a substantial portion of food is lost due to factors such as pests, diseases, adverse weather conditions, and inefficient harvesting practices [13]. In many cases, food is left unharvested because of fluctuations in market prices, labor shortages, or overproduction. For example, in the United States, crops like lettuce, spinach, and broccoli are often plowed back into the soil if market prices fall below profitable levels, resulting in the loss of valuable produce [14]. Similarly, in sub-Saharan Africa, food production losses can be as high as 50% due to pests and disease [15]. These losses contribute to food insecurity in regions where access to food is already limited. The discrepancy between food availability and the inability to deliver it effectively to markets or consumers emphasizes the need for better agricultural practices and market systems that can adjust to demand fluctuations.

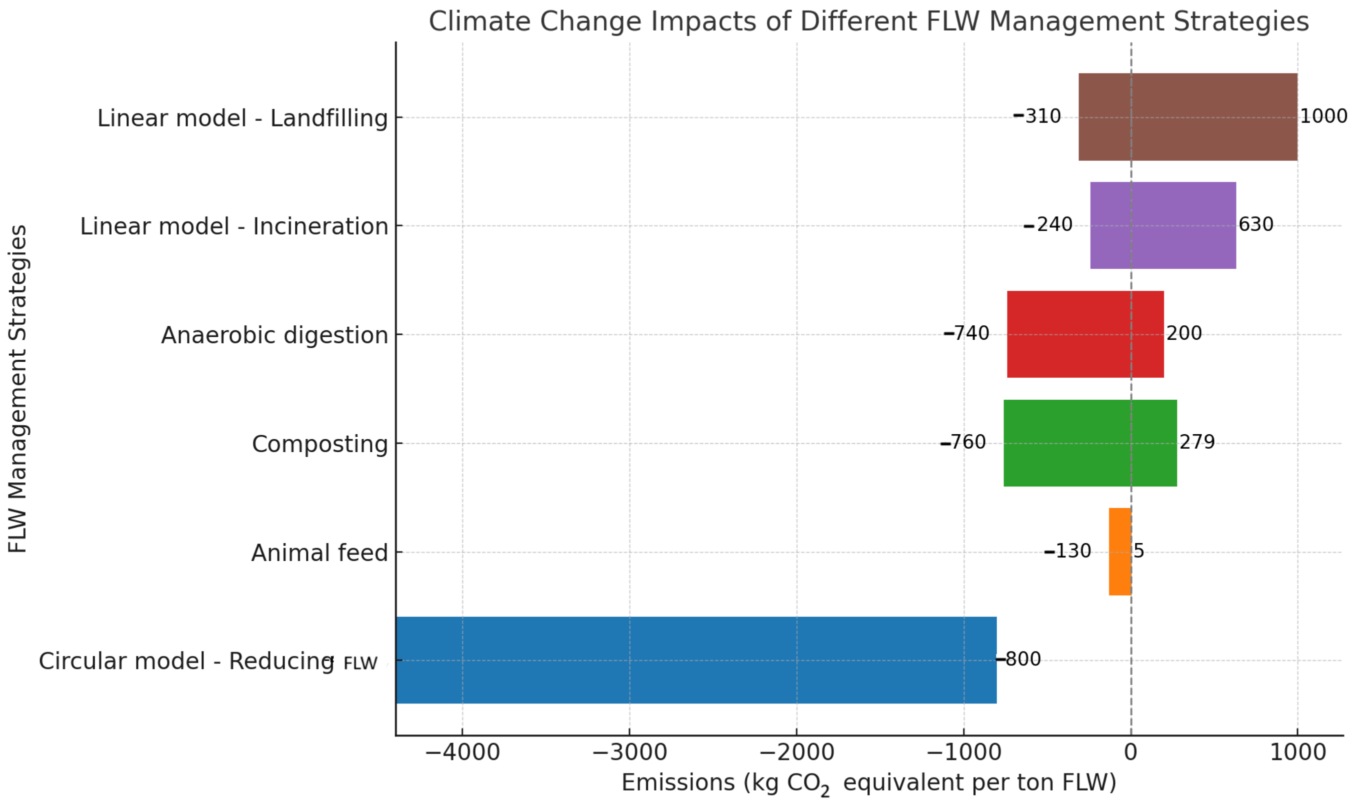

Figure 2. Climate change impacts of different food loss and waste (FLW) management strategies in terms of emissions (kg CO_2 equivalent per ton of FLW). It visualizes the range of emissions for each strategy, with the circular model for reducing FLW having the most significant reduction potential, while landfilling shows the highest emissions in the linear model.

Post-harvest handling also presents significant challenges, especially in developing countries where poor infrastructure and inadequate storage facilities lead to high levels of spoilage. In countries like India and those in sub-Saharan Africa, the lack of cold chain systems—refrigeration for perishable goods—causes large quantities of food, especially fruits and vegetables, to spoil before they can reach consumers [16]. A study conducted by the FAO revealed that up to 40% of fruits and vegetables in sub-Saharan Africa are lost due to improper storage and handling [17]. In India, post-harvest losses of grain are estimated to range from 10% to 20% annually due to the lack of proper storage facilities [18]. These losses highlight the need for investment in infrastructure, such as solar-powered cold storage and efficient transportation networks, to prevent spoilage and extend the shelf life of perishable foods. The food processing and packaging stage also generates significant waste. During processing, a large portion of food is discarded in the form of by-products such as peels, skins, and trimmings. While some of these by-products could be repurposed as animal feed or secondary products, much of it is simply discarded [19]. Cosmetic standards also play a significant role in waste at this stage, as products that do not meet visual or aesthetic requirements are rejected. In the UK, for instance, up to 30% of fruits and vegetables are rejected based solely on their appearance, even though they are perfectly edible [20]. The seafood industry faces similar challenges, with large quantities of by-catch being discarded due to size or quality standards. Innovations in food processing that allow for upcycling, such as turning food by-products into new products like juices, flours, or animal feed, could help reduce waste and make better use of available resources. Retail and distribution channels contribute to food waste through practices such as over-ordering, improper stock management, and strict cosmetic standards for products. Supermarkets and grocery stores in high-income countries often discard produce that does not meet consumer expectations for appearance, even when it is still safe to eat [21]. Additionally, many retailers throw away products that are approaching their sell-by or expiration dates, even though the food may still be safe for consumption. In the US, large quantities of fresh produce are discarded for these reasons. Packaged goods are also wasted due to poor stock rotation practices and overestimated demand. More effective inventory management and consumer education about the differences between "best before" and "use by" labels could help reduce this type of waste. At the consumer level, food waste is the largest contributor to overall waste. According to FAO estimates, households account for 61% of global food waste [18,22]. This includes spoiled food, leftovers, and food that is discarded because of confusion over expiration dates. In high-income countries like the UK, the average household throws away approximately £730 worth of food each year, much of which could have been consumed [23]. In the United States, 30% to 40% of the total food supply is wasted at the consumer level, mainly due to over-purchasing, improper storage, and a lack of understanding about expiration labeling [23,24]. Addressing this issue requires not only consumer education but also efforts to promote better meal planning, food storage practices, and awareness of food labels.

Globally, food waste amounts to approximately 931 million tonnes annually, with households responsible for 61% of that waste, food service sectors contributing 26%, and retail sectors accounting for 13%. The economic cost of this waste is estimated at $1 trillion per year [25]. Table 2 includes the value of the wasted food itself, as well as the resources of water, land, energy, and labor that were used to produce, transport, and dispose of it. Beyond the economic impact, food waste also has significant environmental consequences. Food waste contributes to about 8% of global greenhouse gas emissions, largely due to methane released as organic waste decomposes in landfills. A report from the UN Environment Programme (UNEP) stated that if food waste were a country, it would rank third in greenhouse gas emissions, behind China and the United States [26]. Recent research emphasizes the importance of technological and policy-based solutions to address global food waste. Innovations in cold storage technology, such as solar-powered refrigeration units, are helping to reduce post-harvest losses in regions with unreliable access to electricity [27]. These technologies are particularly beneficial in developing countries where high levels of spoilage occur due to inadequate infrastructure. In addition, precision agriculture techniques that utilize sensors, satellite imaging, and data analytics are allowing farmers to better manage crops, reduce overproduction, and minimize losses due to weather conditions. Upcycling food waste into new products is another emerging strategy to tackle the issue. Companies like ReGrained, for instance, have found innovative ways to repurpose spent grains from the beer brewing process to create nutritious flour for snack bars, adding value to what would otherwise be discarded [28]. Food rescue programs are also gaining traction as a way to redistribute surplus food to those in need. In the US, Feeding America rescued over 2.6 billion pounds of food in 2022, diverting it from landfills and directing it toward communities facing food insecurity [29,30]. These initiatives not only reduce waste but also help alleviate hunger, making them critical components of a sustainable food system. Addressing food waste requires coordinated efforts across the supply chain, from farm to table, involving key stakeholders such as producers, retailers, policymakers, and consumers. Technological innovations, improved infrastructure, better inventory management, and consumer education all play essential roles in reducing waste. Furthermore, supportive policies are critical to creating incentives for waste reduction and encouraging sustainable practices across all levels of the food system. By adopting these strategies, it is possible to significantly decrease the environmental and economic costs of food waste, while also advancing global food security and sustainability.

Table 2. Stages of supply chain and sources of food waste with examples.

Stage of Supply Chain	Sources of Food Waste	Examples	Reference
Agricultural Production	Losses during cultivation due to pests, diseases, weather conditions, inefficient harvesting, and market price fluctuations.	- In the US, crops like lettuce and broccoli are often left unharvested due to falling market prices. - Sub-Saharan Africa loses up to 50% to pests.	[31]
Post-Harvest Handling	Spoilage occurs during transportation and storage due to lack of cold chain infrastructure, particularly in developing regions.	- In Africa, 40% of fruits and vegetables are lost during post-harvest handling. - India loses 10–20% of grain production due to poor storage.	[32]
Processing and Packaging	Waste from trimming, peeling, and off-cuts in food processing. Some by-products are discarded due to cosmetic standards.	- In the UK, up to 30% of crops like fruits and vegetables are rejected for aesthetic reasons. - Seafood waste due to size or appearance criteria.	[33]
Retail and Distribution	Supermarkets discard unsold food that is close to expiration or fails to meet cosmetic standards.	- Retailers discard misshapen produce that does not meet consumer standards. - Expired but still edible goods are often discarded.	[34]
Consumer Level	Households generate food waste through over-purchasing, improper storage, and confusion about expiration dates.	- In the US, 30–40% of the food supply is wasted at the consumer level. - The average UK household wastes £730 worth of food annually.	[35]

4. The Impact of Food Waste on Food Security

Food waste has a profound impact on global food security, which is the ability of all people to have access to sufficient, safe, and nutritious food at all times. While the world produces enough food to feed the entire global population, a staggering 1.3 billion tonnes of food are wasted annually, contributing to hunger and malnutrition [36]. This paradox—where food waste coexists with hunger—underscores the critical connection between food waste and food insecurity, as well as the economic and environmental consequences. Figure 3 illustrates this paradox and highlights the link between food waste and food insecurity.

Figure 3. Impact of food waste on global challenges such as climate change, resource depletion, pollution, poverty, and economic loss.

4.1. Connection Between Food Waste and Hunger

Food waste across the supply chain has the potential to play a pivotal role in reducing hunger, particularly in regions where food insecurity is prevalent. According to the United Nations, nearly 828 million people worldwide are undernourished, with 45 million children suffering from acute malnutrition [37]. A significant portion of the food wasted globally could be repurposed to alleviate these challenges if more efficient systems for food redistribution were in place. Research indicates that recovering just one-quarter of the food currently wasted could feed 870 million people—more than enough to eliminate global hunger [38]. In the United States, food waste amounts to approximately 40 million tonnes annually, while nearly 34 million Americans are food insecure [5]. Food recovery programs such as Feeding America aim to bridge this gap by rescuing surplus food and distributing it to food banks and shelters. Similarly, organizations like Too Good To Go facilitate the redistribution of unsold food from restaurants and grocery stores to consumers at discounted prices. These initiatives highlight the potential of reducing hunger by targeting food waste. Efforts to reduce food waste and its connection to hunger are also underway in Europe. In France, a law mandates that supermarkets donate unsold food to charities, reducing food waste and ensuring surplus food reaches vulnerable populations. This initiative has led to a significant reduction in food waste while simultaneously helping to feed millions of people in need. Additionally, Italy's Food Donation Law encourages food businesses to donate unsold food to those in need, contributing to reduced hunger, particularly in urban areas where food insecurity is prevalent. In developing countries, where hunger is most severe, substantial food losses occur due to factors such as poor infrastructure, inadequate storage facilities, and inefficient transport systems. In sub-Saharan

Africa, for example, post-harvest food losses are particularly high. Studies show that between 7–22% of maize production is lost before it reaches the market in countries like Malawi, Uganda, and Tanzania [39]. These losses are primarily in staples such as grains, fruits, and vegetables—foods that are vital for nutritional security. In India, inadequate cold storage facilities contribute to significant losses of fresh produce, affecting millions of people in rural areas [38]. Investing in better storage facilities, cold chain logistics, and efficient distribution systems could significantly reduce these losses and improve food access, particularly in rural and underserved communities. In Latin America, countries like Brazil and Mexico also face challenges related to food loss and waste. In Brazil, a significant portion of fruits and vegetables is wasted due to inadequate infrastructure for handling and transportation. In response, initiatives such as the Brazilian Food Bank Network have been established to redistribute surplus food to those in need, addressing both food waste and hunger. Similarly, in Mexico, efforts to improve food recovery and reduce losses in supply chains have been gaining traction, particularly in the wake of widespread food insecurity in urban and rural areas [40]. These efforts underscore the need for investments in better infrastructure to reduce food losses and improve food access across Latin America.

4.2. Economic and Environmental Costs

Food waste not only exacerbates hunger but also incurs massive economic and environmental costs. On an economic level, the global cost of food waste is estimated at around $1 trillion annually. This includes the wasted investment in agricultural inputs such as seeds, water, labor, land, and energy, all of which are used to produce food that ultimately is not consumed [40]. In Europe, for example, the cost of food waste is estimated at approximately €143 billion each year. This financial burden affects producers, retailers, and consumers alike, diverting resources that could be used to improve food systems and address global hunger. From an environmental perspective, food waste is a significant driver of greenhouse gas emissions [20]. When food decomposes in landfills, it produces methane—a potent greenhouse gas that is 25 times more effective at trapping heat in the atmosphere than carbon dioxide. According to a report by the FAO, food waste accounts for 8–10% of total global greenhouse gas emissions, meaning it contributes significantly to climate change [41]. For example, a study published in Nature Food in 2021 revealed that food waste leads to the emission of 3.3 billion tonnes of CO_2 equivalent annually, making it one of the largest sources of preventable emissions [42–44]. Furthermore, food production consumes vast amounts of natural resources. An estimated 250 km^3 of water is wasted each year due to food that is produced but not consumed. This is equivalent to the water used by 1.4 billion people annually, highlighting the environmental inefficiencies of food production when waste occurs [42]. Land use is another concern, as approximately 1.4 billion hectares—almost 30% of the world's agricultural land is used to grow food that is ultimately wasted. This wasteful use of land contributes to deforestation, loss of biodiversity, and degradation of ecosystems, all of which have long-term environmental implications [43]. A specific example of the environmental costs associated with food waste is seen in the dairy industry. Milk production is highly resource intensive, with significant inputs of water, feed, and energy required to sustain dairy farms. Yet, in developed countries like the US and UK, milk is one of the most wasted food items, with consumers frequently discarding milk due to confusion over expiration dates. The environmental toll of wasting dairy products includes the unnecessary emissions of greenhouse gases from both the production and disposal of dairy waste [44]. Addressing food waste is thus crucial not only for improving food security but also for reducing the environmental footprint of food systems. Current research underscores the importance of adopting circular economy principles, where food by-products and waste are repurposed and reintegrated into the supply chain. Technologies such as anaerobic digestion, which converts food waste into biogas and organic fertilizers, are gaining traction as sustainable waste management solutions [45]. Additionally, innovations in packaging, such as biodegradable materials and improved labeling practices, are helping to reduce food waste at both the retail and consumer levels. Governments and policymakers also play a critical role in tackling food waste. For instance, France has implemented legislation requiring supermarkets to donate unsold food to charities rather than discarding it, reducing both food waste and hunger [46]. Similarly, in Japan, the Food Recycling Law encourages businesses to recycle food waste into animal feed or fertilizers. These policy frameworks demonstrate how regulatory action can drive positive change by promoting food recovery and recycling efforts [47]. A recent study by Lee et al. (2023) highlights the potential of technology and policy interventions in reducing food waste in urban settings, particularly through the use of digital platforms for food recovery and policy-driven waste management strategies [48].

Food waste is a critical barrier to achieving food security and sustainability. It exacerbates global hunger, imposes substantial economic costs, and contributes significantly to environmental degradation. However, with the right interventions, such as food recovery programs, technological innovations, and supportive policies, food waste can be reduced, unlocking a more sustainable and equitable global food system. Supportive policies refer to governmental and institutional actions aimed at reducing food waste and fostering more sustainable food systems. These policies can take several forms, each designed to address different aspects of food waste reduction, ranging from legislation to incentives and awareness campaigns.

Governments can also offer financial incentives, such as tax breaks or subsidies, to companies that adopt food waste reduction practices or donate surplus food. Additionally, policies that encourage public–private partnerships help coordinate food recovery efforts and improve food distribution, especially to vulnerable populations. Policies that support educational campaigns raise awareness among consumers about the impact of food waste, proper food storage, and the significance of food labels, empowering individuals to make informed decisions and reduce waste at home.

Governments can invest in or incentivize research into new technologies that reduce food waste, such as biodegradable packaging, improved supply chain logistics, or systems that facilitate food recovery and redistribution. Moreover, policies that promote better infrastructure for waste management, such as organic waste composting or anaerobic digestion, support the repurposing of food waste into valuable resources like biogas and fertilizers. Digital platforms and app-based systems, supported by policy frameworks, enable consumers and businesses to recover surplus food more efficiently, promoting food redistribution networks that help tackle urban food insecurity.

Supportive policies are essential because they create a favorable environment for the adoption of food waste reduction practices, foster collaboration across sectors, and encourage long-term sustainability. They complement other efforts such as technological innovations and consumer behavior changes, ensuring a coordinated approach to tackling food waste on a global scale.

5. Transitioning from Biowastes to Resources

The transition from biowastes to valuable resources represents a pivotal opportunity in tackling the dual challenges of food waste and sustainability. With growing awareness of the environmental and economic implications of food waste, innovative approaches are being developed to repurpose biowastes into resources that can contribute to food security, energy production, and environmental restoration [48]. These approaches are grounded in the principles of circular economy, which aim to close the loop by turning waste into new materials, energy, or products. Current research and case studies provide insights into successful biowaste-to-resource initiatives, showcasing how these strategies can be scaled up globally. Figure 4 illustrates key examples of biowaste conversion technologies and their potential applications in sustainable resource management.

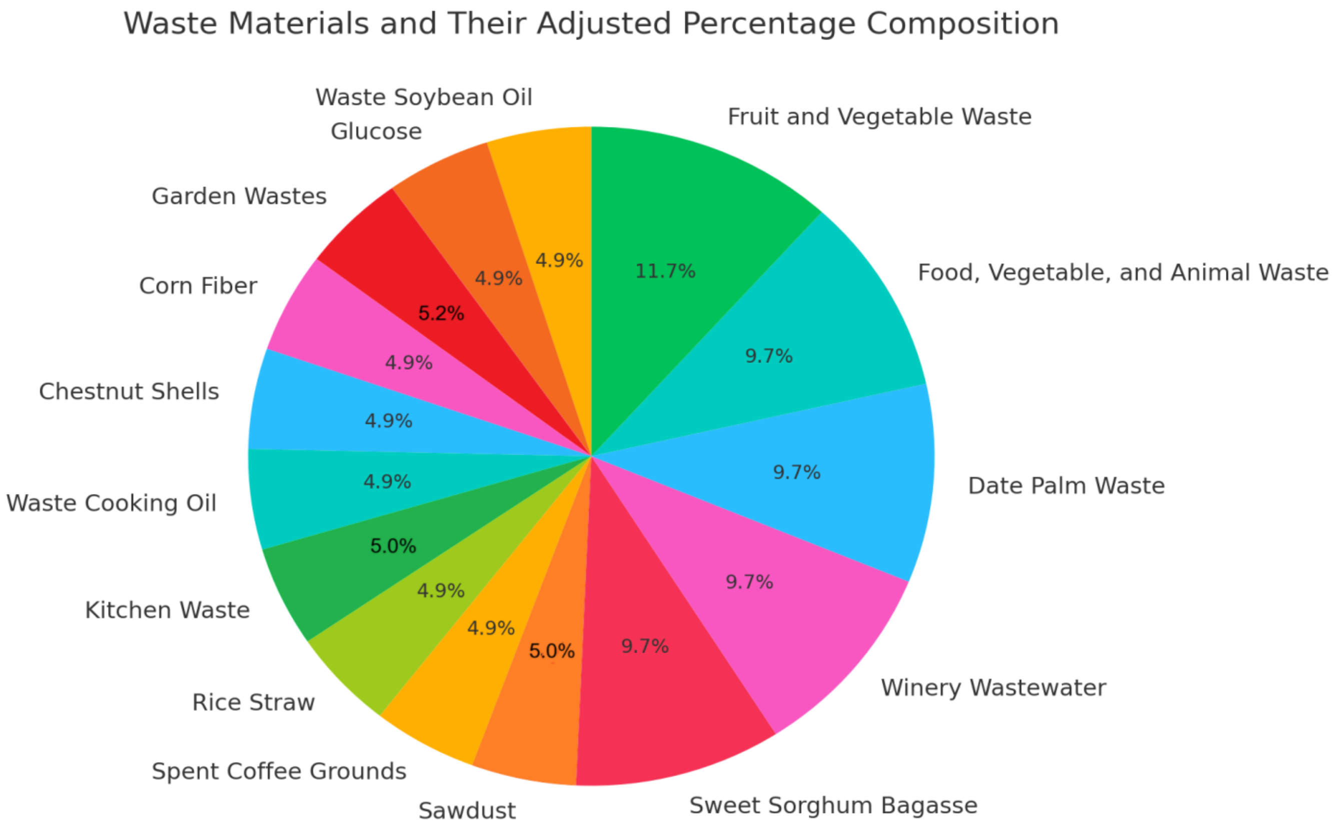

Figure 4. Distribution of various organic wastes by percentage, highlighting the contributions of fruit and vegetable waste (11.7%), food, vegetable, and animal waste (9.7%), and other waste categories in a circular bioeconomy.

5.1. Innovative Approaches to Repurposing Biowastes

One of the most promising approaches to repurposing biowastes is composting, which transforms organic waste into nutrient-rich fertilizers. Composting not only reduces landfill waste but also helps regenerate soil fertility, enhancing agricultural productivity. An example is the use of food scraps and agricultural waste in large-scale composting facilities to produce organic fertilizers for local farms [49]. This method is widely adopted in countries like the Netherlands, where farmers use compost derived from food waste to boost soil health and reduce reliance on chemical fertilizers. Recent studies suggest that using compost can improve soil structure, increase water retention, and support sustainable farming practices by enriching the soil with essential nutrients. Anaerobic digestion (AD) is another key innovation that converts biowastes into energy. In this process, microorganisms break down organic material in the absence of oxygen, producing biogas—a mixture of methane and carbon dioxide—that can be used as a renewable energy source [50]. The remaining material, called digestate, can be used as an organic fertilizer. Anaerobic digestion is increasingly being used to process food waste, sewage sludge, and agricultural by-products. In Denmark, the Maabjerg BioEnergy plant processes over 800,000 tonnes of agricultural waste and manure annually, producing biogas that powers homes and businesses [51]. This closed-loop system reduces greenhouse gas emissions, diverts waste from landfills, and contributes to renewable energy goals. Bioconversion technologies using insects, fungi, or bacteria are emerging as innovative methods for transforming food waste into valuable products [52]. One of the most notable examples is the use of black soldier fly larvae (BSFL) to break down organic waste [53]. The larvae feed on food waste and convert it into high-protein feed for livestock and fish, while also producing compostable residues. Research published in Waste Management in 2022 highlights that BSFL bioconversion can reduce the volume of organic waste by up to 60%

within a week, making it an efficient and sustainable waste management strategy. This technique is particularly relevant in regions with large volumes of food waste and high demand for animal feed, such as Southeast Asia and parts of Africa [53,54]. Upcycling is also gaining traction, especially in the food industry. This process involves transforming food by-products or surplus into new food products, reducing waste while creating value-added items. For instance, the company ReGrained uses spent grains from the beer brewing process to produce flour, which is then used in nutritious snack bars. Similarly, Rubies in the Rubble, a UK-based company, creates condiments from surplus fruits and vegetables that would otherwise go to waste [55]. Upcycling initiatives not only prevent food waste but also introduce new, sustainable products to the market, tapping into consumer demand for environmentally friendly options.

5.2. Case Studies: Successful Biowaste-to-Resource Initiatives

One of the most successful examples of biowaste-to-resource transformation is Sweden's waste-to-energy program. In Sweden, over 99% of household waste is recycled or converted into energy through waste-to-energy (WtE) plants [56]. Food waste, in particular, is processed through anaerobic digestion to produce biogas, which is used to power public transportation and heat homes. In 2022, Sweden's WtE program was able to generate enough biogas from food waste to power over 260 buses in Stockholm, significantly reducing the reliance on fossil fuels [57]. This model of converting biowaste into energy serves as an example of how waste management strategies can be effectively integrated into national sustainability goals. Another notable example is the Bio-bean initiative in the UK, which converts spent coffee grounds into biofuels. Every year, an estimated 500,000 tonnes of coffee grounds are generated in the UK, much of which ends up in landfills, releasing methane gas as it decomposes [58]. Bio-bean collects these grounds from coffee shops and restaurants and processes them into biomass pellets, which are then used as a renewable energy source in industrial boilers. According to a 2021 report by Energy Technology, Bio-bean's recycling process reduces greenhouse gas emissions by up to 80% compared to traditional waste disposal methods [59].

This initiative highlights how niche waste streams can be leveraged to produce energy while reducing environmental impact. In India, the Ecozen Solutions initiative demonstrates how biowaste can be transformed into resources for smallholder farmers. Ecozen focuses on providing solar-powered cold storage systems to reduce post-harvest food losses. In rural India, up to 30% of fruits and vegetables are lost due to inadequate storage, but Ecozen's cold rooms, powered by solar energy, help extend the shelf life of perishable produce [60]. The project not only reduces food waste but also provides farmers with more time to sell their products at favorable market prices, improving food security and livelihoods. A 2023 study by Agricultural Systems found that Ecozen's technology reduced food spoilage by 25% in participating regions, significantly enhancing the sustainability of agricultural supply chains [60]. In Brazil, the Sucafina initiative is making strides in repurposing sugarcane waste. Sugarcane bagasse, the fibrous residue left after sugar extraction, is traditionally burned as a waste product, contributing to air pollution. However, Sucafina has developed a method to convert sugarcane bagasse into bioplastics, reducing the need for petroleum-based plastics [61]. This initiative is part of Brazil's broader efforts to advance bio-based materials and reduce plastic pollution. A recent study published in Biomass and Bioenergy in 2023 highlighted the potential of sugarcane bagasse to produce biodegradable packaging materials, offering a sustainable alternative to traditional plastics [62]. These case studies illustrate the potential of transforming food and agricultural waste into valuable resources, contributing to both sustainability and economic development. As the global population continues to grow, and the pressure on natural resources intensifies, the need for innovative biowaste-to-resource solutions will become increasingly important. Research shows that by adopting these approaches, global food systems can become more resilient, reducing waste, conserving resources, and enhancing food security for future generations.

6. Technologies and Strategies for Biowaste Conversion

Biowaste conversion technologies play a crucial role in addressing the environmental challenges posed by organic waste by transforming it into valuable resources like energy, fertilizers, and food products. These innovative approaches support the goals of a circular bioeconomy and promote sustainable development. In recent years, stakeholders involved in organic waste management—both in developed and developing nations—have shifted away from traditional, end-of-pipe waste management strategies, such as landfilling and incineration, which were often implemented with minimal controls [63]. Instead, the focus has moved towards environmentally friendly technologies, including composting and anaerobic digestion. These methods are now widely adopted for managing organic waste in a more sustainable manner. Furthermore, emerging technologies like solid-state fermentation have gained significance within the framework of a circular economy [63]. These methods, primarily applied to biodegradable organic materials, align well with the principles of a circular bioeconomy by enabling waste materials to be repurposed rather than discarded.

6.1. Composting and Soil Enrichment

Composting is a well-established method for converting organic waste, including kitchen scraps, yard waste, and agricultural residues, into nutrient-rich compost. This natural decomposition process enhances soil structure, increases water retention, and boosts nutrient content, making it an effective soil enrichment strategy [63]. Composting also reduces the volume of waste sent to landfills, thereby mitigating greenhouse gas emissions. In 2023, the UK's Green Bin initiative composted over 5 million tons of household organic waste. The resulting compost was used in local farms and gardens, reducing the need for chemical fertilizers. This initiative helped the UK divert 40% of its food waste from landfills, contributing to the country's sustainability goals [64].

6.2. Bioconversion Technologies

Bioconversion technologies employ microbial, enzymatic, or chemical processes to convert biowaste into high-value products such as biofuels, biofertilizers, and bioplastics. Anaerobic digestion, for example, breaks down organic waste in the absence of oxygen to produce biogas, which can be used as renewable energy [65]. The solid by-product, digestate, is a valuable organic fertilizer. The Ductor Corporation, a Finnish bioconversion company, operates a biogas plant in Mexico that converts poultry waste into biogas and organic fertilizers [66]. In 2023, the plant processed 40,000 tons of poultry manure, generating enough biogas to power 10,000 homes. The project also produced 6000 tons of organic fertilizer, supporting sustainable agriculture in the region [67].

6.3. Recycling and Upcycling into Novel Food Products

Upcycling food waste into new products is an innovative strategy for reducing food waste and creating value from by-products. This approach transforms surplus food or food processing by-products into functional ingredients, new food products, and beverages. Recycling food waste into edible goods not only reduces waste but also minimizes the environmental impact of food production [67]. The US-based company Renewal Mill upcycles by-products from the plant-based milk industry into high-protein, gluten-free flours. In 2023, the company processed 150,000 tons of okara (soy pulp), which would otherwise be discarded, into flour for baking and packaged snacks. This strategy has helped reduce food waste in the US by converting it into profitable and sustainable food products [68].

6.4. Pyrolysis and Biochar Production

Pyrolysis is a thermochemical process that heats organic waste in the absence of oxygen, producing biochar, a carbon-rich material, along with bio-oil and syngas. Biochar can be used to improve soil fertility, sequester carbon, and reduce greenhouse gas emissions.

This method not only diverts waste from landfills but also creates materials that benefit agriculture and carbon capture initiatives [69]. In 2022, the Australian company Earth Systems set up a pyrolysis plant capable of processing 10,000 tons of forestry waste annually. The plant produced over 2000 tons of biochar, which was applied to farmlands to enhance soil fertility and carbon sequestration [70]. This process contributes to reducing the environmental footprint of agricultural practices while addressing waste management challenges.

6.5. Black Soldier Fly (BSF) Bioconversion

Bioconversion with insects, particularly black soldier fly (BSF) larvae, is an innovative approach for handling food and agricultural waste. BSF larvae are highly efficient at consuming organic waste, converting it into protein-rich biomass suitable for animal feed. Additionally, the residual byproduct, known as frass, can be repurposed as organic fertilizer. For instance, Insectta, a farm in Singapore, uses BSF larvae to process up to 10 tons of food waste daily, generating both high-protein feed and organic fertilizer. In 2023 alone, the farm produced over 300 tons of BSF protein powder, intended for aquaculture and poultry feed, as well as 500 tons of organic fertilizer to support local agriculture [71]. This process not only tackles food waste but also provides sustainable alternatives to conventional feed and fertilizers. Studies have shown that the duration of fermentation of food waste (FW) prior to feeding it to BSF larvae can influence yield. Fermentation periods ranging from 0 to 10 days were tested, with an 8-day fermentation producing optimal results. At this stage, the FW displayed a lower pH and higher microbial diversity, which slightly enhanced larval biomass, reaching approximately 222 mg per larva. Most groups achieved peak larval biomass after 10 days of bioconversion. Fermentation significantly altered the microbial composition of FW, marked by an increase in the abundance of unclassified_f_Clostridiaceae and a decrease in Lactobacillus [72]. Throughout the bioconversion process, dynamic and mutualistic microbial interactions developed between the BSF larvae gut microbiome and the FW substrate, leading to reciprocal modifications. Notably, unclassified_f_Clostridiaceae abundance rose in the BSFL gut, whereas it was initially present at very low levels (<1%) in the larvae. Despite these microbial shifts, a stable core microbiome was consistently observed in the BSFL gut across all samples [72]. This core microbiome was primarily composed of nine genera, with Enterococcus and Klebsiella as the dominant groups. This stability in the core microbiome, alongside microbial adaptations in response to the FW substrate, demonstrates the complex and adaptive nature of BSFL in organic waste bioconversion. Table 3 illustrates the impact of fermentation duration on BSF larvae growth and microbial composition in the food waste bioconversion process.

Table 3. Innovative technologies and strategies for converting biowaste into valuable products.

Technology	Description	Applications	Reference
Composting	A natural process of recycling organic matter, such as food scraps and agricultural waste, into nutrient-rich compost for soil enrichment.	- Urban food waste composting for community gardens - Large-scale composting for organic farming	[6]
Anaerobic Digestion	Biological process in which microorganisms break down organic waste in the absence of oxygen, producing biogas and digestate (used as fertilizer).	- Biogas production from household and industrial organic waste - Digestate for soil enrichment	[73]
Vermicomposting	The use of earthworms to decompose organic waste, producing vermicompost, a nutrient-rich fertilizer, and vermiliquid, used for crop production.	- Vermicomposting kitchen waste at the household level - Large-scale vermicomposting systems in agriculture	[74]

Table 3. *Cont.*

Technology	Description	Applications	Reference
Bioconversion Technologies	Conversion of organic waste into valuable products (biofuels, biofertilizers, and animal feed) using insects, fungi, bacteria, or enzymes.	- Black soldier fly larvae converting food waste into animal feed - Mushroom cultivation on agro-waste	[75]
Pyrolysis	Thermal decomposition of organic material at high temperatures in the absence of oxygen, producing biochar, bio-oil, and syngas.	- Biochar from agricultural waste used to improve soil health - Pyrolysis of food processing waste to produce bio-oil	[76]
Upcycling Food Waste	The process of converting food waste or by-products into new, higher-value food or non-food products, reducing waste and creating economic opportunities.	- Spent grain from beer brewing upcycled into flour for snack bars - Fruit peels converted into edible coatings	[77]
Lignocellulosic Biomass Conversion	Breakdown of plant biomass (e.g., agricultural waste) into biofuels and bio-based chemicals using chemical, biological, or mechanical methods.	- Conversion of corn stover into bioethanol - Enzymatic breakdown of wood chips to produce bio-based chemicals	[78]

7. Challenges and Barriers

The conversion of biowaste into valuable resources offers tremendous opportunities for sustainability and resource efficiency. However, several challenges and barriers hinder the widespread adoption of these technologies. Below are the key challenges categorized into technological and economic issues, as well as regulatory and policy barriers, with relevant examples and current data.

7.1. Technological and Economic Challenges

While biowaste conversion technologies have advanced significantly, many still face technological and economic hurdles that limit their large-scale implementation. Some technologies require high upfront costs, complex infrastructure, and specialized expertise, which can be a deterrent for widespread adoption. Additionally, biowaste processing efficiency varies based on waste composition, posing technical challenges for optimizing bioconversion processes. One major technological challenge is the variability in feedstock quality for bioconversion. In AD plants, inconsistent waste composition (e.g., from municipal solid waste) leads to inefficiencies in biogas production. According to a 2023 report by the European Biogas Association, over 30% of AD plants in Europe face operational issues due to feedstock variability, reducing the energy output and increasing maintenance costs [79]. Additionally, the initial capital investment for AD plants ranges from €2 to €5 million, making it economically unviable for smaller communities and businesses without government subsidies or external funding [80]. Another example of economic challenges is the high cost of converting biowaste into biofuels, such as biodiesel and ethanol. The production of advanced biofuels is often more expensive than fossil fuels, partly due to the technology required to break down complex organic materials like lignocellulose [81]. A 2023 study by the International Renewable Energy Agency (IRENA) showed that while biofuels have the potential to reduce greenhouse gas emissions by 80–90%, their costs are currently 30–50% higher than conventional fuels, limiting their commercial viability without significant subsidies or incentives [82].

7.2. Regulatory and Policy Barriers

A lack of clear and consistent regulations, as well as inadequate policy support, is a significant barrier to biowaste conversion efforts. In many countries, the regulatory frameworks surrounding biowaste management are either outdated or fragmented, making it difficult for businesses to navigate compliance issues. Additionally, insufficient incentives or inconsistent enforcement of waste management policies slow down the development and adoption of biowaste conversion technologies. In India, despite significant efforts to promote waste-to-energy projects, regulatory hurdles remain a major barrier. A report from 2023 by the Centre for Science and Environment (CSE) highlighted that nearly 60% of the planned waste-to-energy plants were delayed due to unclear guidelines on feedstock standards and environmental compliance [83]. Additionally, the absence of streamlined waste segregation at the source has limited the effectiveness of bioconversion technologies, as mixed waste reduces the efficiency of processes like composting and anaerobic digestion. Another example of regulatory barriers is the European Union's (EU) strict regulations on food waste-derived products [84]. Despite the potential for upcycling food waste into new food products, stringent food safety regulations make it difficult for companies to market products made from upcycled ingredients. A 2022 report from the European Commission acknowledged that unclear regulations on food waste-derived products have stifled innovation in the circular food economy, with over 50% of start-ups in the sector facing delays or rejections in product approvals due to regulatory uncertainty [85]. Moreover, the lack of standardized policies across regions also hampers international collaboration and trade in biowaste products. For instance, the export of biochar, a byproduct of pyrolysis, is restricted in several countries due to varying environmental standards and certification processes, limiting market opportunities for producers.

8. The Role of the Circular Economy in Food Security

A circular economy aims to design out waste and keep materials in use for as long as possible. In the context of food security, a circular economy can minimize food loss and waste, optimize resource efficiency, and reduce environmental impacts, all while ensuring that the global population has access to sufficient, safe, and nutritious food. The integration of circular economy principles into the food system can address inefficiencies in the current linear model and enhance global food security.

8.1. Integrating Circular Economy Principles

The integration of circular economy principles into food systems focuses on reducing waste, optimizing resource use, and closing nutrient loops. This can be achieved through waste prevention, innovative recycling methods, and the upcycling of food waste into valuable products. At each stage of the food supply chain—from production and processing to distribution and consumption—there are opportunities to reduce food loss and waste. One notable initiative is the European Union's Farm to Fork strategy, introduced in 2020, which incorporates circular economy principles into food production [86]. This strategy emphasizes the importance of reducing food loss and waste, encouraging the reuse of by-products from food processing, and promoting sustainable agricultural practices. By 2023, the EU had already achieved a 10% reduction in food waste across member states, with ambitious goals to halve food waste by 2030 [32]. This has helped ensure more efficient use of resources, thus contributing to improved food security in the region. Another example comes from the Netherlands, where farmers and food companies have adopted circular farming practices. Crop residues are used as animal feed, while manure from livestock is repurposed as fertilizer, closing the loop between crop and livestock production. In 2023, the Netherlands achieved an 8% reduction in the use of synthetic fertilizers, while maintaining high levels of food production, demonstrating how circular practices can enhance food security by making agricultural systems more resilient and sustainable [87].

8.2. Benefits of a Closed-Loop Food System

A closed-loop food system, where resources are continuously cycled back into the system, provides numerous benefits to food security, including reducing food waste, enhancing resource efficiency, and mitigating the environmental impacts of food production. By reusing and recycling organic materials, a closed-loop system can improve soil health, enhance biodiversity, and reduce reliance on finite natural resources, all of which contribute to more sustainable food production and long-term food security. In Japan, the implementation of a closed-loop system in the city of Kamikatsu showcases the benefits of such an approach [88]. The city has achieved a recycling rate of over 80% by composting food waste and using it as fertilizer for local farms. This initiative has reduced landfill use and enhanced soil fertility, boosting local food production. In 2023, the city reported a 30% increase in crop yields due to improved soil quality from compost application, helping to strengthen food security at the local level [89]. Another significant benefit of a closed-loop food system is the ability to transform food waste into new food products, thus contributing to food availability. In the UK, the start-up Rubies in the Rubble uses surplus fruits and vegetables to make condiments such as chutneys and ketchups [90]. In 2022, the company rescued over 200 tons of food waste, reducing the amount of food discarded while providing affordable and nutritious food products [91]. This model demonstrates how closing the loop on food waste can contribute to food security by reducing the strain on food resources and making better use of available materials.

9. Sustainability Impacts

The sustainability impacts of biowaste conversion and circular economy practices extend across environmental, economic, and social domains. By reducing the reliance on landfills, minimizing greenhouse gas emissions, and fostering community-level economic development, these practices contribute significantly to long-term sustainability. Below are key areas where biowaste conversion technologies deliver positive sustainability outcomes.

9.1. Environmental Benefits: Reducing Landfill and Emissions

One of the most significant environmental benefits of biowaste conversion is the reduction in waste sent to landfills. Organic waste in landfills decomposes anaerobically, generating methane, a potent greenhouse gas with a global warming potential 25 times greater than carbon dioxide [92]. Diverting biowaste from landfills through composting, anaerobic digestion, and recycling significantly reduces methane emissions and contributes to climate change mitigation. Additionally, these processes convert waste into valuable by-products such as compost and bioenergy, reducing the need for chemical fertilizers and fossil fuels, thus lowering the overall carbon footprint [92]. The European Union has implemented stringent regulations on waste management under the Waste Framework Directive, aiming to limit organic waste in landfills. As a result, by 2023, the EU achieved a 55% reduction in organic waste sent to landfills compared to 2010 levels, preventing the release of over 10 million tons of CO_2-equivalent emissions [93]. In Germany, biogas plants have played a key role, processing over 100 million tons of organic waste annually, producing renewable energy and reducing methane emissions from landfills. Another environmental benefit comes from the use of biochar in agriculture. Produced via pyrolysis of organic waste, biochar sequesters carbon in soils, helping to mitigate climate change. Studies in 2023 showed that biochar application on farms in Australia resulted in a 20% reduction in nitrous oxide emissions, while improving soil fertility and crop productivity [94].

9.2. Economic and Social Impacts on Communities

Biowaste conversion also delivers economic and social benefits, particularly for local communities. By creating new business opportunities in waste collection, processing, and upcycling, these technologies generate jobs and stimulate economic development. Small-scale farmers and entrepreneurs can benefit from selling compost, biogas, and other biowaste-derived products. Moreover, reducing waste management costs through biowaste valorization helps local governments and municipalities save on landfill fees and waste treatment expenses [60]. In Indonesia, the Bandung Waste-to-Energy project, launched in 2022, has had a transformative economic impact on the local community. The project processes over 2000 tons of waste per day, producing electricity for 50,000 households and creating 1200 jobs in waste collection, processing, and plant operation. This initiative not only provides renewable energy but also generates income for low-income families involved in the waste supply chain, significantly improving the local economy [47]. On a smaller scale, social enterprises such as Too Good To Go in Europe have built entire business models around preventing food waste. In 2023, the company expanded to over 17 countries, rescuing 50 million meals and creating new jobs across the food distribution network [95]. This not only reduces food insecurity by making affordable meals available to those in need but also raises awareness about food waste in local communities. Furthermore, community composting programs have been shown to improve social cohesion by involving residents in environmental sustainability initiatives. In New York City, the Department of Sanitation's NYC Compost Project has engaged over 1 million residents in composting efforts. In 2022, the project diverted 25,000 tons of organic waste from landfills, providing free compost to local community gardens and urban farms, thereby enhancing food production and building stronger community bonds [96].

10. Future Perspectives and Policy Recommendations

The future of biowaste-to-food initiatives holds immense promise for addressing global sustainability challenges, especially in the areas of waste management, food security, and climate change mitigation. To fully unlock the potential of these initiatives, robust policy frameworks are essential. These frameworks must support innovation, encourage investment, and ensure equitable access to resources for all stakeholders. Below are key policy recommendations that could drive the successful implementation of biowaste-to-food initiatives.

10.1. Policy Frameworks for Supporting Biowaste-to-Food Initiatives

10.1.1. Incentivizing Biowaste Conversion Technologies

Governments should implement policies that provide financial incentives for businesses, municipalities, and individuals to adopt biowaste-to-food technologies. This can include tax breaks, grants, and low-interest loans for setting up composting facilities, anaerobic digestion plants, and upcycling initiatives. Additionally, feed-in tariffs and subsidies for bioenergy production from waste can make biogas and biofuel projects more economically viable, encouraging wider adoption of these technologies. In Denmark, the government's policy framework for biogas production offers financial incentives through guaranteed feed-in tariffs for biogas producers [97]. By 2023, this policy contributed to the establishment of over 160 biogas plants, which process organic waste and convert it into energy. The framework has supported a 20% increase in renewable energy generation from biowaste between 2015 and 2023, helping Denmark achieve its sustainability goals [98].

10.1.2. Supporting Research and Development (R&D)

Investments in R&D are crucial to improving the efficiency, scalability, and economic viability of biowaste-to-food technologies. Governments can establish funding programs to support research on new bioconversion techniques, upcycling innovations, and waste-to-energy technologies. Collaborative research efforts between universities, businesses, and government agencies should be promoted to accelerate technological advancements and optimize existing processes for diverse waste streams. The European Union's Horizon Europe program allocated €1 billion in 2023 for research and innovation related to circular bioeconomy projects, including biowaste conversion technologies [99]. Several projects funded under this initiative focus on developing new techniques for converting agricultural and food processing waste into high-value products such as proteins, biofuels, and biodegradable materials. These R&D investments are essential for enhancing the competitiveness of the biowaste sector and fostering sustainable solutions.

10.1.3. Implementing Mandatory Food Waste Reduction Targets

To support the transition to biowaste-to-food systems, policymakers should establish mandatory food waste reduction targets. Such targets can create a strong incentive for businesses, especially in the food and hospitality sectors, to prevent food waste and adopt circular economy practices. Coupled with penalties for excessive food waste and rewards for waste reduction achievements, these policies can drive significant progress toward sustainable waste management. In 2023, France introduced a law requiring food businesses, including supermarkets and restaurants, to donate unsold food to charities or face fines [33]. As a result, France reduced its food waste by 30% within two years of implementing the law. Additionally, more than 300,000 tons of surplus food were donated to food banks, supporting efforts to improve food security and reduce waste simultaneously.

10.1.4. Promoting Public–Private Partnerships (PPPs)

Public–private partnerships are essential for scaling up biowaste-to-food initiatives and ensuring that they are economically viable and widely adopted. Governments can foster collaboration between private companies, municipalities, and non-governmental organizations (NGOs) to establish joint ventures in waste processing and food production. PPPs can share financial risks, pool resources, and promote innovative business models for biowaste management and conversion. In 2022, the city of San Francisco, in partnership with Recology (a private waste-management company), launched a composting program that processes food waste from households and businesses [100]. The organic waste is converted into nutrient-rich compost, which is sold to local farms. This public–private collaboration has diverted over 200,000 tons of organic waste from landfills annually and improved soil health in the region, demonstrating the effectiveness of PPPs in implementing circular economy strategies.

10.1.5. Harmonizing International Standards for Biowaste Products

To enable global trade and encourage the adoption of biowaste-to-food technologies, policymakers should work towards harmonizing international standards for biowaste-derived products, such as compost, biochar, and upcycled food products. This can reduce barriers to entry for businesses and promote cross-border collaborations, ensuring that the benefits of biowaste conversion are widely shared [101]. Establishing common quality standards, safety regulations, and certification processes will also build consumer trust and facilitate the marketing of biowaste-derived goods. In 2023, the International Organization for Standardization (ISO) introduced guidelines for compost quality, helping to standardize the production of organic fertilizers from biowaste [102]. Countries like Canada, Japan, and Brazil have adopted these guidelines to regulate their composting industries, ensuring high-quality and safe products for agriculture [103]. These standards are crucial for promoting the global market for biowaste-derived products and fostering international cooperation in the circular economy.

11. Conclusions

The transformation of food waste into valuable resources is a crucial step in addressing global food security challenges and promoting environmental sustainability. By leveraging biowaste as a bioresource, we can close the loop in food systems, reduce reliance on landfills, minimize greenhouse gas emissions, and optimize the use of natural resources. This transition from a linear, wasteful model to a sustainable, circular approach ensures that food is not only produced and consumed efficiently but also repurposed in ways that benefit the environment and communities. The integration of biowaste conversion technologies such as composting, anaerobic digestion, and upcycling into food systems demonstrates the potential for creating a more resilient, resource-efficient future. In doing so, food waste is transformed into energy, fertilizers, and new food products, contributing to soil health, renewable energy generation, and nutrient recycling. By adopting circular economy principles, we can improve food production, ensure more equitable distribution of food, and mitigate the environmental impacts of food loss and waste. For this transition to succeed, supportive policy frameworks are critical. Governments, industries, and communities must work together to promote innovative biowaste conversion technologies, foster public–private partnerships, and incentivize sustainable practices. The implementation of clear regulations, international standards, and research investments will help accelerate the shift towards a bio-based, circular economy that enhances food security while safeguarding the planet for future generations. In conclusion, the journey from food waste to food security is a pathway towards sustainability. By treating food waste as a resource rather than a burden, we can build more robust, environmentally friendly food systems that provide for both people and the planet. This transition is not just a necessity but an opportunity to rethink how we value our resources and work collectively towards a zero-waste future.

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