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COMPOSTING OF VEGETABLE WASTE: CASE STUDIES AND ANALYSIS OF USED EQUIPMENT

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Abstract: The composting of plant waste is an essential ecological solution for the sustainable management of organic waste. This article focuses on analyzing the equipment used in the composting process of plant waste, with a particular emphasis on case studies and the assessment of different system efficiencies. A comparison is made between traditional and modern equipment, identifying the best solutions in terms of performance, cost–effectiveness, and environmental impact, thus contributing to the widespread adoption of composting practices. Choosing the appropriate equipment is essential for obtaining high–quality compost, which can be used as an organic fertilizer. Various types of composting equipment are analyzed, including mechanical composters, composting tunnels, and vermicomposting systems. In addition to their economic efficiency, their environmental impact is also assessed, highlighting the reduction of energy consumption and greenhouse gas emissions. The obtained results emphasize the importance of using advanced technologies to optimize the composting process, integrating automated systems, and utilizing sensors to monitor essential compost parameters. These innovations contribute to improving equipment performance and expanding large–scale composting practices. In conclusion, the development and implementation of efficient equipment are crucial for the sustainable management of plant waste. The widespread use of such equipment can significantly reduce the volume of waste sent to landfills and produce valuable organic fertilizers, supporting the transition towards a circular economy.

Keywords: composting, vegetable waste, composting equipment, equipment efficiency

1. INTRODUCTION

Composting of vegetable waste plays a crucial role in sustainable waste management by transforming organic material into nutrient–rich compost. This process not only enhances soil quality but also reduces the environmental impact of vegetable waste [1, 2]. Given the increasing global concern regarding organic waste—particularly that originating from fruits and vegetables—composting provides an effective strategy for recycling plant–based matter and mitigating environmental degradation [3, 4].

Vegetable waste, due to its high biodegradability and nutrient content, is especially suitable for composting [5, 6]. Research has investigated various composting technologies, ranging from traditional methods such as windrow and in–vessel composting to advanced techniques like rotary drum composting and hyperthermophilic composting. These modern systems improve the decomposition process by enhancing temperature regulation and stimulating microbial activity [7, 8]. Studies have shown that incorporating bulking agents, such as rice bran, and using microbial inoculants can significantly improve aeration, microbial diversity, and overall compost quality [9, 10]. Furthermore, optimizing aeration and turning frequency is crucial—especially in decentralized systems—for increasing microbial activity and composting efficiency [11, 12]. Beyond traditional composting, the management and valorization of agricultural residues, including vegetable waste, have become increasingly important in sustainable agricultural practices. The integration of biorefinery techniques holds promise for converting agro–industrial by–products into valuable materials, thus promoting resource recovery and minimizing environmental impact [13, 14]. Composting agricultural residues not only contributes to soil health but also supports emerging markets for high–value products, such as those derived from agro–bioenergy processes [14]. Parameter optimization plays a pivotal role in improving the efficiency and sustainability of composting processes. Numerous studies have explored strategies to adjust conditions such as

temperature, moisture, aeration, and microbial dynamics to enhance the final product's quality and its environmental benefits [15, 16]. The thermophilic phase, characterized by elevated temperatures, is particularly critical for the effective decomposition of vegetable waste, as it promotes pathogen elimination and accelerates organic matter breakdown [17, 18]. The need for tailored waste management approaches to effectively treat fruit and vegetable waste in urban environments has also been emphasized [19].

The development and optimization of composting equipment is equally vital to improving process efficiency. Different composting systems—such as windrow, in-vessel, and rotary drum composters—offer unique advantages depending on the operational scale and waste characteristics [20, 21]. By refining the design and operation of composting systems—especially in aspects such as aeration, temperature control, and rotation—researchers and practitioners can significantly enhance both compost quality and decomposition efficiency [9, 22]. This contributes to sustainable agriculture by enabling the effective transformation of organic waste into high-quality compost, which in turn improves soil fertility and promotes environmental sustainability [23, 24]. This review provides an overview of composting technologies and equipment, including case studies and key insights that emphasize the role of technological innovation in advancing sustainable waste management and agricultural practices.

2. MATERIALS AND METHODS

This paper is based on an extensive review of scientific literature, including peer-reviewed journal articles, conference proceedings, technical reports, books, and other credible online sources. All materials were carefully selected, studied, and analyzed to extract the most relevant information on vegetable waste composting technologies and equipment.

The focus was placed on evaluating several composting methods—such as windrow, in-vessel, rotary drum, and aerated static pile composting—highlighting their operational characteristics and performance. Key parameters considered in the analysis include temperature dynamics, moisture control, aeration techniques, the use of microbial inoculants, and the quality of the final compost (C:N ratio, pH, organic matter content).

In addition to the literature study, case studies describing real-world applications of composting systems were consulted to better understand equipment efficiency, energy consumption, and environmental impact. The comparative analysis aimed to identify the most efficient and sustainable composting equipment suitable for processing vegetable waste. All consulted sources are properly cited in the text and listed in the reference section.

3. RESULTS

Rapid urbanization and population growth have intensified the pressure on waste management systems, highlighting the urgent need for efficient and sustainable strategies, particularly for the treatment and recycling of organic waste. Among these, vegetable waste—generated by households, markets, restaurants, and agricultural activities—constitutes a major component of the organic waste stream and offers significant potential for resource recovery [25].

Due to its high biodegradability, vegetable waste is well-suited for composting, a key process in the circular economy that transforms organic refuse into nutrient-rich compost. This compost improves soil structure, reduces the dependency on chemical fertilizers, and promotes environmentally friendly agricultural practices [26].

Biological treatments such as composting and anaerobic digestion not only yield valuable organic fertilizers but also contribute to lowering greenhouse gas emissions. The European Union's mandate for separate biowaste collection plays a vital role in optimizing organic waste valorization, particularly in rural and semi-urban contexts where centralized treatment facilities may be lacking. This article focuses on vegetable waste composting, analyzing critical process parameters—such as temperature, moisture content, oxygen availability, and the carbon-to-nitrogen (C/N) ratio—that

influence compost quality and decomposition efficiency. It also explores the range of technologies and equipment used in various composting systems, from small-scale household setups to large industrial operations. Case studies presented in the literature reveal a broad spectrum of practices adapted to different geographical and institutional contexts. These studies demonstrate not only the agronomic and environmental advantages of composting but also the technical, economic, and regulatory challenges associated with implementing such systems [27, 28].

Despite its clear benefits, composting processes are not without drawbacks. They can emit greenhouse gases—such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—as well as volatile organic compounds (VOCs), with emission levels influenced by factors including aeration, temperature, and pH. These emissions may pose risks to environmental and human health. Nevertheless, a range of mitigation strategies, including biofiltration, compost covering, biochar amendment, and microbial inoculation, have been shown to reduce emissions and improve the sustainability of composting operations [29].

The hospitality and food service sectors are also significant contributors to food waste, further emphasizing the need for effective waste management solutions in commercial contexts. Composting has proven to be a viable and environmentally sound approach for handling this waste. In many cases, on-site composting is particularly beneficial, as it reduces the need for collection and transportation, thereby decreasing the sector's environmental footprint and operational costs [30].

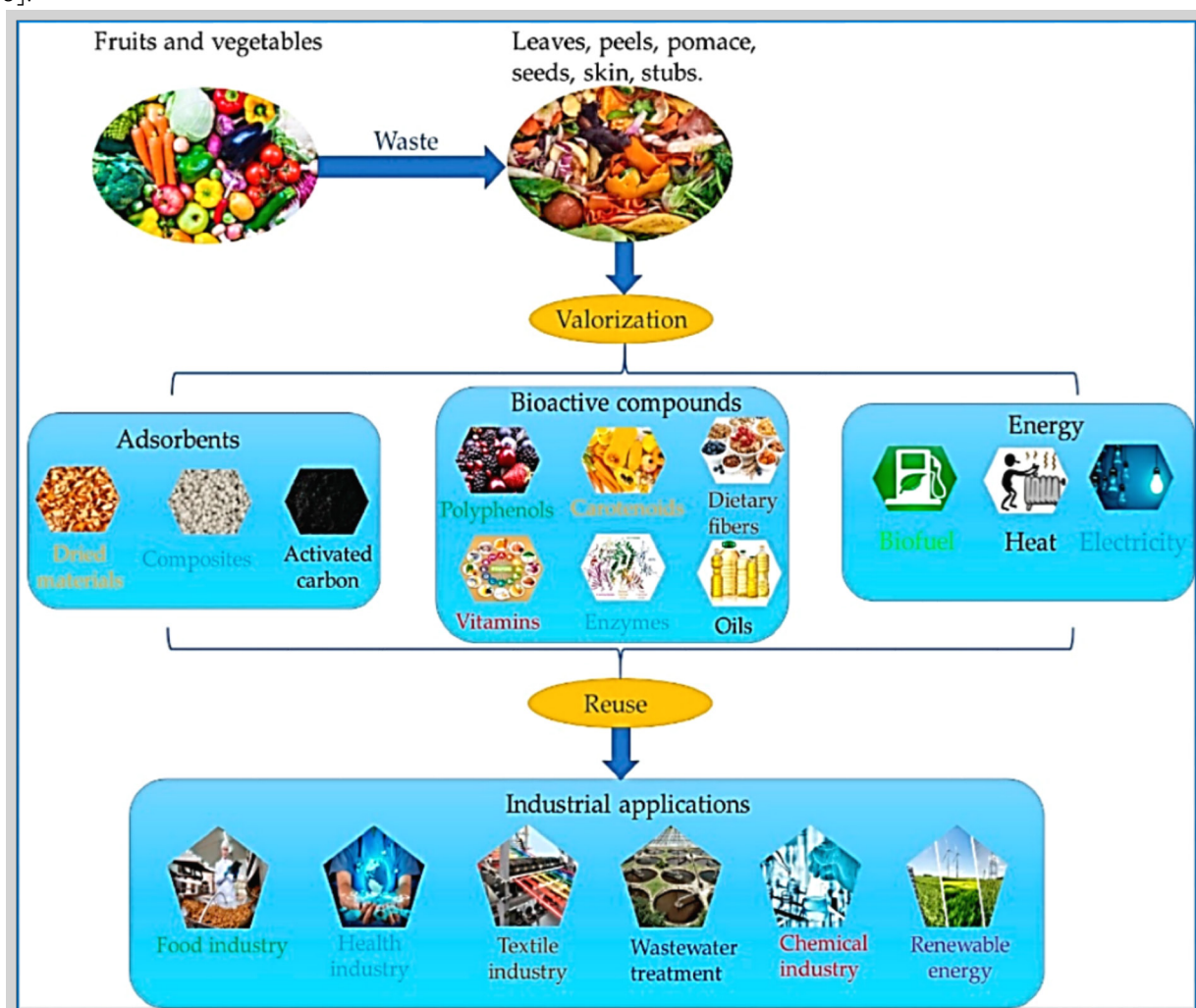


Figure 1 – Potential valorization pathways of fruit and vegetable waste (FWW), highlighting an integrated circular economy approach [31].

The image presents an integrated approach to the valorization of fruit and vegetable waste, showcasing its transformation into valuable products such as adsorbents, bioactive compounds, fibers, oils, and energy. These by-products have applications in various industries including food,

cosmetics, animal feed, pharmaceuticals, and water treatment. In addition to these high-tech recovery pathways, composting remains a fundamental and accessible method of recycling organic waste. It plays a vital role in converting fruit and vegetable residues—such as peels, pulp, seeds, and skins—into nutrient-rich compost that enhances soil health and supports sustainable agriculture. As part of the circular economy, composting complements advanced extraction technologies by managing residues that are not suitable for biochemical recovery, ensuring that no part of the waste stream goes unused. This synergy between composting and value-added recovery exemplifies an efficient, eco-friendly strategy for organic waste management.

Composting has proven to be an effective and sustainable method for managing organic waste, with significant environmental, economic, and social benefits. In the case of vegetable waste, composting not only transforms organic material into valuable compost but also contributes to reducing greenhouse gas emissions and minimizing the environmental footprint of waste management systems. A significant example of this is the co-composting of vegetable waste, such as the residues from the food processing industry or from urban gardens, which has been demonstrated to improve both compost stability and agronomic value. By combining vegetable waste with other organic materials, such as manure or green waste, the process produces more stable organic compounds, increases water retention, and enhances nutrient profiles suitable for agricultural applications [32, 33].

4. TECHNICAL ASPECTS OF COMPOSTING

In urban environments, local composting systems have also shown great potential. For instance, food service units, such as restaurants in Bucharest, have integrated compact composting systems into their operations. Through the use of efficient composting equipment and staff training in waste management, these businesses have achieved up to a 60% reduction in organic waste volume, while also minimizing the carbon footprint associated with waste transportation and landfill disposal. The compost produced is utilized for urban green spaces or donated to community gardens, helping to promote circular economy principles and engage citizens in sustainable practices [34].

However, achieving high-quality compost remains a challenge, especially when dealing with pathogens like *Escherichia coli* and *Salmonella* spp., which can compromise the safety of compost for agricultural use. Effective pathogen control requires monitoring key composting parameters such as temperature, moisture, oxygen levels, and the carbon-to-nitrogen (C/N) ratio. Research suggests that maintaining temperatures above 55°C for extended periods can effectively kill pathogens, while a balanced C/N ratio of 25–30:1 supports optimal composting conditions [35].

Recent studies have also highlighted the role of plant-based waste not only as a substrate for composting but also as a source of bioactivators. Microbial inoculants such as lactic acid bacteria (*Streptococcus*, *Leuconostoc*, *Lactobacillus*, and *Pediococcus*) have been shown to accelerate the composting process and suppress soil-borne pathogens, offering a promising strategy for improving compost quality and cost-effectiveness [36].

While composting holds great potential, challenges remain in terms of its widespread implementation. In the European Union, only 26% of biowaste is currently separately collected, with the rest being either landfilled or incinerated, which leads to the loss of valuable resources and increased pollution [37]. As of January 2024, EU regulations mandate the separate collection of biowaste in all Member States, thus encouraging the use of composting technologies [38]. Additionally, the anaerobic digestion sector, which often complements composting, has created thousands of jobs and contributes significantly to reducing emissions and producing renewable energy [39]. The harmonized implementation of the European Union's Waste Framework Directive (2008/98/EC) plays a crucial role in advancing the adoption of composting practices. This legislation mandates the separate collection of biowaste, yet varying national approaches to transposition,

administrative capacity, and infrastructure development continue to hinder the full potential of organic waste recovery in many EU countries [40].

Efficient composting requires the adaptation of recipes based on the physicochemical characteristics of raw materials. Vegetable waste, such as fruit and vegetable peels, typically contains a high water content (80–90%) and requires strict control over the carbon-to-nitrogen (C/N) ratio and moisture levels [24]. The final quality of the compost depends on its stability and maturity. In the absence of uniform European standards, existing indicators, such as the germination index, may be insufficient to guarantee optimal compost quality [41].

5. INTERNATIONAL PERSPECTIVES AND BEST PRACTICE EXAMPLES

Globally, composting approaches vary depending on socio-economic contexts and local conditions:

- In Asia, where organic waste constitutes between 25–70% of municipal solid waste, composting is increasingly adopted as a cost-effective and scalable solution. In countries like India and Indonesia, local governments and communities are recognizing the potential of composting to mitigate the growing waste crisis and reduce reliance on landfills [42, 43]. Composting initiatives have also been integrated into urban agriculture, supporting local food production and enhancing urban sustainability.
- In the United Arab Emirates, an optimal mix of 40% grass and 20% insoluble polymers has proven effective in maintaining moisture levels and reducing the processing time for composting. This innovative approach has helped address challenges related to high temperatures and limited organic waste availability, making it a valuable model for regions with similar climatic conditions [44].
- Decentralized models have been particularly effective in cities in developing countries, where community engagement and low costs are key factors. In places like Accra, Ghana, local composting programs have empowered communities to take ownership of waste management while generating valuable organic fertilizers for local agriculture. These initiatives demonstrate the potential for sustainable waste management systems in resource-constrained environments [45].
- In the United Kingdom, limited infrastructure and a focus on green waste have hindered the efficiency of existing composting systems. There is a growing need for expanding composting facilities to include food waste, which makes up a significant portion of municipal solid waste. Without a broader scope for composting, the UK risks missing out on potential environmental benefits, such as reduced landfill use and lower greenhouse gas emissions [46].

These international examples highlight the diverse approaches to composting and the importance of adapting practices to local contexts. While challenges remain, particularly in terms of infrastructure and community involvement, successful case studies demonstrate that composting can be a key solution in achieving both environmental and socio-economic goals.

Integrating Social and Economic Dimensions into Composting Systems

The success of modern composting systems depends not only on technological factors but also on key social components such as environmental education, the involvement of local authorities, and public trust in source separation practices [47].

In many developing regions, particularly across Asia, urban compost is often utilized in peri-urban agriculture. However, the full potential of this practice is contingent upon supportive public policies and institutional frameworks [48].

In urban and academic settings, several initiatives have demonstrated how composting can transform food waste into valuable resources while contributing to sustainability and economic efficiency. For example, at Kean University in New Jersey, an in-vessel composting system processed 1,000 lbs of food waste daily, converting it into compost used on campus grounds. This

initiative not only diverted waste from landfills but also generated an annual profit of \$13,200, reduced greenhouse gas emissions, and minimized the need for synthetic fertilizers [49].

Similarly, at the University of A Coruña (UDC) in Spain, two decentralized composting systems—a static home composter (SHC) and a dual system combining decentralized composting and static composting (DC–SC)—were installed to treat canteen food waste. These systems produced compost with a C/N ratio between 9 and 15, fully compliant with Spanish quality standards, and reached maturity within 2 to 4 months. The case exemplifies how decentralized urban composting can support sustainable agriculture and serve as an effective waste management strategy in institutional environments [50].

These examples highlight the importance of integrating social, economic, and policy dimensions into composting strategies to ensure both environmental sustainability and long-term operational success.

Sustainability Assessments and Life Cycle Analysis (LCA)

Life Cycle Assessment (LCA) studies indicate that composting methods can be effectively complemented by anaerobic digestion and waste-to-energy incineration, especially in integrated waste management systems [51, 52]. These approaches allow for optimized recovery of organic waste while minimizing environmental impacts. In Southern Italy, for example, the “windrow” composting method has proven to be both environmentally sustainable and economically viable, particularly in the context of organic farming systems [53]. Such low-input, open-air systems are suitable for rural regions where land and labor are more readily available.

Relevant Case Studies

An analysis of international case studies reveals a broad range of effective composting strategies for plant-based waste, each tailored to specific economic, technological, and institutional contexts. Composting has shown remarkable adaptability to different geographic and climatic conditions, as well as infrastructure levels. The reviewed case studies highlight the agronomic and ecological benefits of compost use—such as improved soil health and reduced reliance on chemical fertilizers—while also identifying practical limitations, including insufficient policy support, technological gaps, and limited public engagement. These findings emphasize the need for context-specific solutions and supportive frameworks to maximize the sustainability potential of composting practices.

In South Korea, strict public policies—such as volume- or weight-based waste taxation and a ban on landfilling biodegradable waste—have led to the recycling of over 90% of food waste [54]. In the retail sector, automated thermophilic composting has proven effective in processing fruit and vegetable waste, reducing costs and increasing operational efficiency [55]. Additionally, the recovery of bioactive compounds from this waste supports circular economy principles and presents opportunities for various industries [31].

In Northwestern Europe, a study focused on Flanders (Belgium) identified 28 key barriers to composting adoption on intensive farms. These were categorized as:

- financial and market-related (high costs, limited biomass access),
- political and institutional (restrictive regulations),
- technological (inconsistent compost quality, lack of equipment), and
- informational and behavioral (lack of knowledge and experience).

Despite these challenges, compost use showed significant benefits for soil organic carbon, water retention, and biodiversity. Policy recommendations included regulatory simplification, farmer training, and equipment subsidies [56].

In urban environments, composting has proven viable for managing municipal organic waste. In Ecuador, market and urban gardening residues were successfully composted using lignocellulosic blends, resulting in stable, phytotoxin-free compost suitable for agriculture [57].

Technology and equipment selection proved essential. For example, a 3.5 m³ rotary composter achieved temperatures up to 70°C, enabling rapid organic matter degradation. Final treatments like windrow composting and vermicomposting produced high-quality compost in as little as 20 days.

At the University of A Coruña (Spain), a decentralized system for composting university canteen waste was developed. Static composting (≤ 20 kg/day) and a combined dynamic–static system (for higher volumes) were compared. The dynamic–static system produced mature compost in 2–4 months, meeting Spanish Class A standards with a C/N ratio of 9–15, highlighting the potential of decentralized composting in sustainable urban agriculture [50].

In Crete (Greece), a composting project using tomato, cucumber, and olive leaf waste—integrated into an educational program—achieved temperatures over 55°C and produced pesticide-free compost with acceptable electrical conductivity (3–15 mS/cm), suitable for agricultural use.

Another study evaluated five types of composting reactors, including a household-scale complete-mix system enhanced with fungal-based microbial accelerators (*Trichoderma* spp., *Aspergillus* spp., *Paecilomyces* spp., *Chaetomium globosum*) and mature compost as inoculum. Key parameters influencing compost quality included composting duration, temperature, C/N ratio, moisture, and NPK content [58].

In Southeast Asia, composting of vegetable waste mixed with 2.5% poultry manure in a 37 L passive aeration reactor produced high-quality compost [18].

In Saudi Arabia, where food waste accounts for over 50% of municipal waste, composting has been proposed as a sustainable solution. Enhancing compost quality with natural zeolite and biochar could yield annual savings of over USD 70 million [59].

Life cycle assessment (LCA) has been used to compare waste management strategies. LCA provides comprehensive insight into the environmental impact of composting versus alternatives like incineration or anaerobic digestion [60].

Following the analysis of case studies on the composting of plant residues, several key trends and conclusions have been identified regarding the technologies used and the efficiency of the equipment. These conclusions are supported by data obtained from various case studies and are presented in the table below:

Table 1. Efficiency Analysis of Equipment Used for Composting Plant Residues

Equipment	Type of Composting	Composting Efficiency	Operating Cost	Time Required to Complete the Process	Additional Benefits
Rotary composter	Aerobic	80–90%	Medium	3–4 weeks	Uniform mixing of material, fast processing
Static composter	Aerobic	70–80%	Low	6–8 weeks	Low cost, easy to use
Anaerobic composting system	Anaerobic	60–75%	High	8–12 weeks	Efficient under high-moisture conditions

Conclusions based on the results

The reviewed studies demonstrate that composting is a versatile and effective strategy for organic waste management across diverse geographic, agricultural, and urban contexts. Success relies heavily on proper technology selection, microbial control, and supportive policies.

Based on the results presented in the analysis, each type of composting equipment presents specific advantages and disadvantages. For instance, rotary composters offer the highest efficiency in terms of processing time and material uniformity but come with higher operating costs compared to static composters. Conversely, anaerobic systems operate more slowly but are effective under specific moisture conditions and offer greater long-term durability.

Composting not only reduces waste volume and environmental impact but also generates valuable agricultural inputs and contributes to circular economy goals. However, broader adoption requires

overcoming financial, regulatory, and educational barriers—challenges that must be addressed through integrated policy development and infrastructure investment.

6. CONCLUSIONS

The composting of vegetable waste plays a key role in sustainable organic waste management, contributing to environmental protection, greenhouse gas reduction, and soil resource regeneration. The analysis of composting systems—from traditional methods like aerated piles and bin composting to advanced technologies such as in-vessel systems, rotary drum composters, and aerated static piles—highlights the importance of selecting appropriate equipment based on waste volume, implementation environment, and available resources.

Case studies demonstrate that while traditional methods remain viable for small-scale operations due to their lower costs, modern equipment with automated control of temperature, moisture, and aeration is better suited for large-scale or urban composting. These technologies increase efficiency, shorten decomposition time, improve compost quality, and reduce environmental impact.

The integration of sensors and automated monitoring systems enhances process stability and product consistency, while also lowering operational costs and health risks. Moreover, such innovations align with the principles of the circular economy by fully valorizing vegetable waste as a reusable resource.

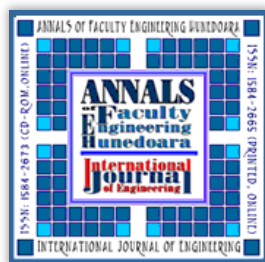
In conclusion, investing in innovative and efficient composting equipment is essential for expanding sustainable composting practices. Future research should focus on improving energy efficiency, reducing operational costs, and developing accessible solutions for various socio-economic contexts, thereby maximizing the potential of vegetable waste within a regenerative economy.

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