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Review

The Management of Food Waste Recycling for a Sustainable Future: A Case Study on South Korea

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Abstract: South Korea has made remarkable progress in food waste recycling through efficient policies. Around 30% of total waste is food waste, with over 90% of it effectively separated and collected. Challenges remain in optimizing biogas production and utilizing food waste for animal feed. The Volume-Based Waste Fee system, initiated in 1995, reduced waste and promoted recycling. In 2005, the ban on direct food waste landfilling further encouraged separation and proper disposal. The Master Plan for Reducing Food Wastes, launched in 2010, led to the nationwide implementation of the Weight-Based Food Waste Fee (WBFWF) system in 2013. Drawing inspiration from Japan's policies and strengthening them with the WBFWF system, South Korea has evolved its food waste management. It also adapted European policies to enhance its regulations. This review provides a valuable waste management framework for countries seeking to improve their recycling and resource utilization initiatives.

Keywords: food waste; animal feed; recycling; resource recovery; Weight-Based Food Waste Fee system; South Korea

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1. Introduction

The Sustainable Development Goals (SDGs) are gaining global attention amid worries regarding food resource security and environmental pollution stemming from the expansion of the global economy and population growth. This underscores the significance of the circular economy concept, aimed at optimizing resources and reducing waste. The UN's Sustainable Development Goal (SDG) 12.3 addresses the serious social and environmental impacts of food loss and waste due to indiscriminate consumption [1]. According to the United Nations Environment Program (UNEP) Food Waste Index, 1.3 billion tons of food is lost or wasted worldwide every year. Also, the Intergovernmental Panel on Climate Change (IPCC) indicated that the greatest contributor to global warming is anthropological CO_2 emissions, and emphasized the urgent need to limit them worldwide [2,3]. In 2015, in response to the climate change crisis, the United Nations Climate Change Conference urged that carbon neutrality should be realized by 2050 [4]. Tonini et al. [5] emphasized that one of the major contributors to global warming is food waste generated in the household and food-service sectors. The disposal of food waste in landfills is a primary factor that adversely affects greenhouse gas emissions due to the production of methane through anaerobic decomposition [6–8].

In 1995, South Korea introduced a waste management system known as the Volume-Based Waste Fee (VBWF) policy, which is based on the 'pay-as-you-throw-principle', wherein fees are determined based on the quantity of waste disposed of through the sale of required standard garbage bags. This policy has been considered to be an effective method for measuring the amount of generated waste and managing waste collection and treatment processes [9–13]. However, the policy did not focus on the differentiation of food waste from general waste, leading to approximately 30% of food waste being mixed into VBWF garbage disposal bags [14]. During the disposal process, the decomposition of these organic materials (e.g., direct landfilling without separating household non-food waste from food waste) resulted in the emission of unpleasant odors, and the liquid portion from these wastes seeped into the adjacent soil, leading to contamination of the landfills and the surrounding areas [15].

A committee located near the landfills initiated efforts to prevent wet food waste from entering these sites in November 1996. They strictly prohibited any moisture-laden garbage disposal bags, whether from their contents or contamination in garbage vehicles. As part of these efforts, municipalities across the region and the nation adopted measures for food waste reduction, including the Comprehensive Food Waste Plan in December 1996 and the Basic Plan for Food Waste Resource Utilization in September 1998 [16].

In addition to these measures, cities nationwide implemented a ban on the direct burial of food waste in landfills, commencing in January 2005 [15]. The Master Plan for Reducing Food Wastes was introduced in 2010 to facilitate the implementation of a comprehensive Weight-Based Food Wastes Fee (WBFWF) system, which was subsequently enforced nationwide in 2013. This food waste disposal system has evolved to include standard bags, adhesive stickers, and radio frequency identification (RFID)-based weight measurement methods [17].

This review introduces the historical trajectory of waste management policies in South Korea, shedding light on how management systems for food waste have evolved alongside policy shifts. In addition, the method and current status of food waste treatment were addressed and an effective strategy for sustainable waste management was presented. Specifically, we describe the following: (1) the effectiveness of establishing a management system according to changes in food waste disposal policies; (2) the WBFWF method as a successful case of food waste management and recycling being applied in the field; (3) the resource utilization of food waste in South Korea; and (4) the methods of resource utilization including composting, animal feed, and biogas production. The purpose of this review is to provide a comprehensive analysis of the history of food-waste management policies in South Korea which can serve as a framework for developing effective policies in other countries.

2. Methodology

This paper provides a description and review of relevant information related to South Korea's waste policies, focusing on the historical background, food waste-related policies and methods, and the current state of food waste management. Additionally, it conducts a review of the utilization and status of food waste. The methodology involves analyzing environmental reports, waste management statistics, relevant legislations, and scholarly articles. It outlines significant policy changes and their present status, and aims to present an effective framework for efficient food waste management strategies applicable to other countries.

3. Waste Management Acts and Policies in South Korea

The policies established by the Ministry of Environment regarding food waste in South Korea can be categorized as follows: (1) the introduction of a Weight-Based Food Wastes Fee (WBFWF) system, and (2) policies for the resource recovery of food waste.

3.1. Changes in Acts and Policies by Era

The development of waste management systems in South Korea can be divided into four periods: The Filth Cleaning Act (1961–1977), Environmental Conservation Act (1978–1986), Waste Management Act (1986–1992), and Division (1993–present) [18]. A summary of the chronological changes in South Korea's legislation and policy development related to waste management is shown in Figure 1.

3.1.1. Filth Cleaning Act (1961–1977)

In the 1960s and 1970s, the Filth Cleaning Act was established in South Korea, which was intended to focus on waste management using the concept of cleaning. During this period, there was a significant shift from the previous focus on waste and sewage treatment to regulations mandating the cleaning of industrial waste by businesses. This has alleviated environmental problems caused by urbanization and the burden of waste disposal on local governments [19]. In this act, "garbage" included solid waste, ash, sludge, manure, and animal residue. The owners of land or buildings within the cleaning zone were obliged to clean up the garbage on their premises, and the garbage that was difficult for individuals to manage was collected and disposed by the district, city, or county. In addition, provisions were made to prohibit the illegal dumping of garbage, implement comprehensive cleaning measures, and impose penalties [20]. The act of dumping waste in other public areas such as sewers, parks, port areas, rivers, etc., has been revised to impose penalties of up to 6 months of imprisonment or fines of up to 0.3 million won [21].

3.1.2. Environmental Conservation Act (1978–1986)

With an increase in social interest regarding the environment, the Environmental Conservation Act was enacted in 1978. This Act initiated an environmental management system that emphasized the need to establish environmental standards, implement environmental impact assessments, and create environmental technology review committees [22]. Environmental standards were established for air and water quality, stipulating that the concentration of sulfur dioxide (SO_2) in air should be managed to not exceed 0.05 ppm. Water quality was categorized based on various living environments, ranked as Grades 1, 2, 3, and 4 for drinking, industrial, agricultural, and aquatic waters, respectively. The management criteria were defined using various measures, such as pH, chemical oxygen demand (COD; mg/L), biochemical oxygen demand (BOD; mg/L), dissolved oxygen (DO; mg/L), and the most probable number (MPN/100 mL) of coliform bacteria [23].

In response to the escalating pollution problems resulting from industrial and societal advancement, the Environmental Agency was established in 1980 [24]. This agency has a comprehensive range of responsibilities, including addressing air and water pollution, vehicular emissions, waste management, soil contamination, marine pollution, environmental impact assessments, and ecological surveys [18].

3.1.3. Waste Management Act (1986–1992)

The Waste Management Act was enacted in 1986, and integrated the Filth Cleaning and Environmental Conservation Acts to introduce and include the concept of recycling. The Filth Cleaning Act focused primarily on the regulations related to the disposal of waste and sewage, whereas the Environmental Conservation Act aimed to address air and water pollution resulting from industrialization. However, this did not explicitly represent the fundamental objective of waste management. The amended Waste Management Act of 1991 defined the responsibilities of the national government and local authorities, based on a new waste classification system. Waste was classified into two categories based on the type of disposal facility: household and business wastes. Business waste was further divided and managed according to the standards of the emission facilities (e.g., air and water quality and noise). Household waste was defined as waste other than business waste [18].

3.1.4. Division (1993–Present)

From 1993 to present, the era of division laws and more detailed management approaches are being developed. The first policies on food waste were introduced during this period. Since 1998, there has been extensive discussion regarding the disposal of food waste, culminating in the formulation of the Basic Plan for Reducing Food Waste and Resources (1998–2002). This policy was implemented by delineating roles among key stakeholders at each stage of production, distribution, and consumption. In addition, the composting and conversion of food waste into animal feed were promoted through the resource conversion plan [25].

In 2005, a law prohibiting the direct landfilling of food waste was enacted, and in 2013, the WBFWF policy was introduced. Comprehensive food waste measures during the years of 2004 to 2007 focused on establishing a food waste management infrastructure and improving the operation of food waste treatment facilities. Food conversion improvement and comprehensive food waste measures for 2006 to 2010 aimed to promote the reduction in food waste while expanding and enhancing treatment facilities [26]. In the first phase of the Basic Plan of Resource Circulation (2018–2027), the goal is to reduce the daily generation of household waste per capita while increasing the adoption rate of RFID (Radio Frequency Identification) for food waste in multi-unit dwellings to 100% by 2027. The target rate for the anaerobic digestion of food waste to bio-gasification has been revised upwards from 10% in 2018 to 36% by 2027 [27]. The Act on the Promotion of the Production and Use of Biogas Using Organic Waste Resources (Act No. 19151) was enacted and promulgated on 30 December 2022. This law stipulates the scope of mandatory private biogas producers, biogas production target rate, and targets of financial support [28].

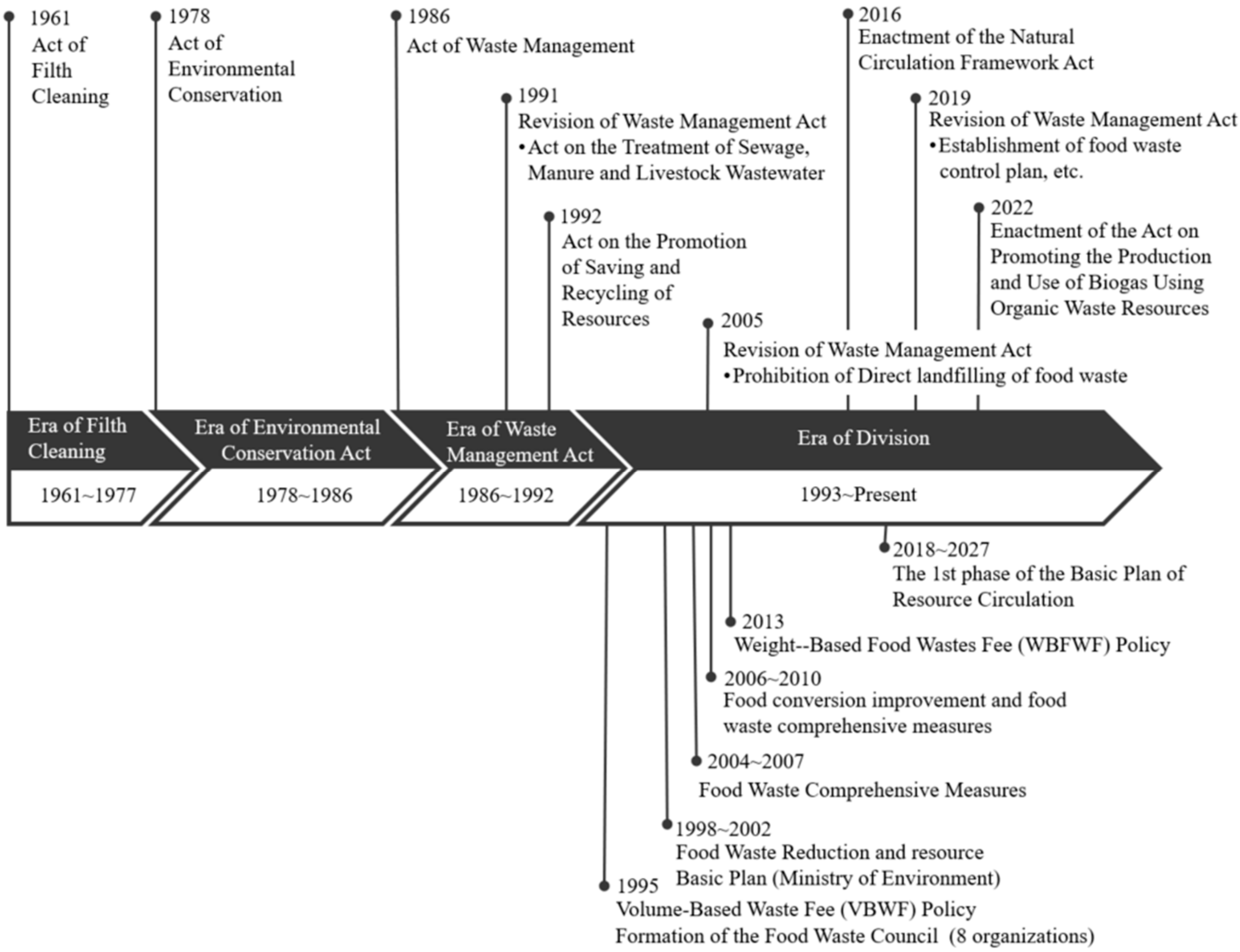


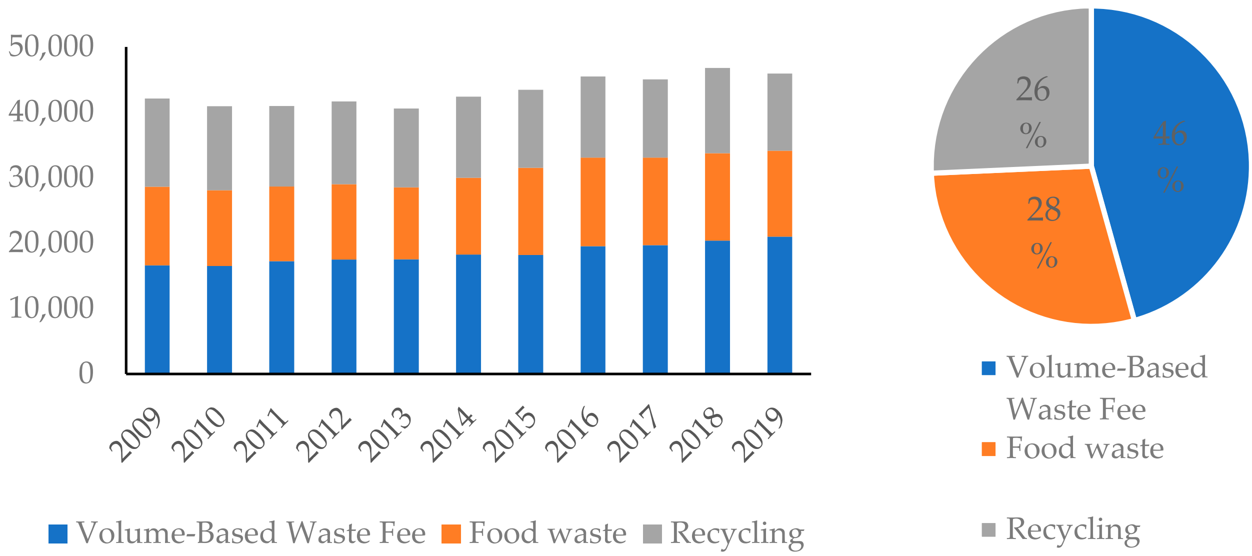
Figure 1. Changes in laws and policies regarding waste management in South Korea by era [18,19,26].

4. The Generation and Management of Food Waste

4.1. Food Waste Disposal and Classification

In South Korea, garbage classification is primarily divided into three categories: VBWF, Food Waste, and Recycling Waste. Food Waste includes agricultural, fishery, and food leftovers generated during the production, distribution, and cooking processes. Recycling Waste comprises plastics, cans, glass bottles, paper, and scrap metal, which should be separately discharged for recycling. All other general waste is placed in VBWF garbage bags for disposal.

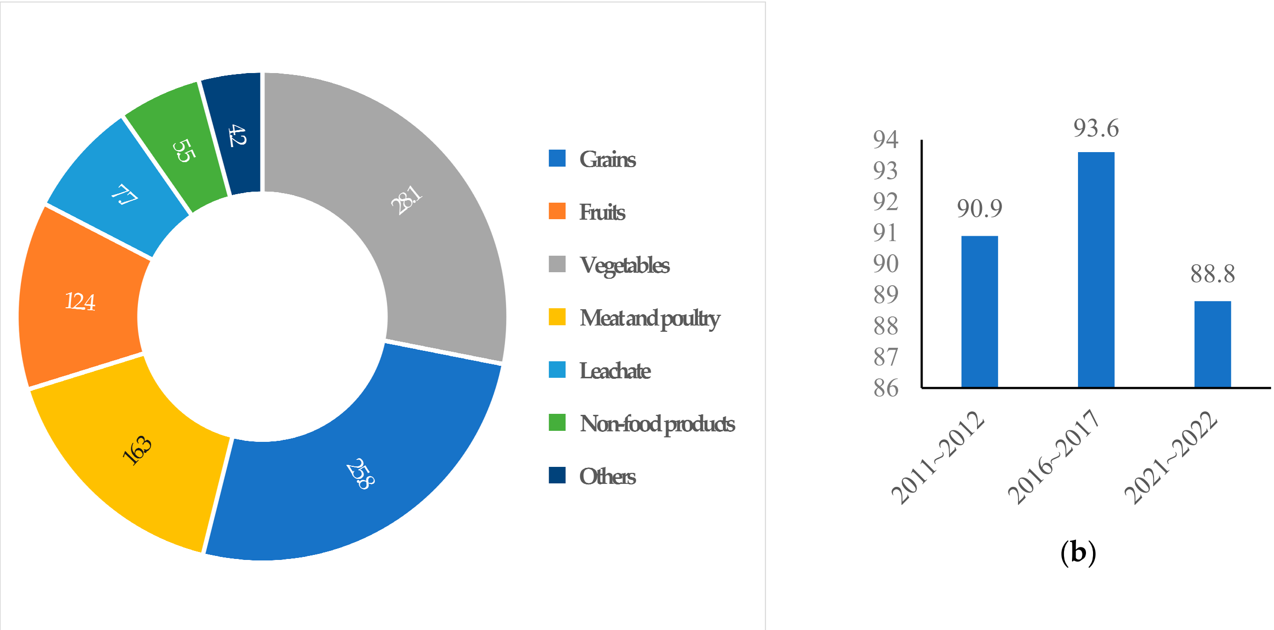
The annual waste generation in South Korea has increased consistently since 2013 (Figure 2). In particular, the VBWF and food waste were 16% greater in 2019 compared with that in 2013. As a result, policies related to food waste management have been highlighted, and the need to curb the increase in food waste generation and promote the recycling of generated food waste is being emphasized [29].



(**a**) (**b**)

Figure 2. National waste discharge volume: (**a**) national waste discharge volume (tonnes/day) and (**b**) 2019 waste discharge volume ratio (%) [27].

In 2019, considering the nationwide waste generation ratio, VBWF, food, and recyclable waste accounted for 20,917, 13,138, and 11,802 tonnes per day, respectively. Food waste accounted for 28% of the total waste generated in 2019. Notably, 53.0% of the food waste was from households and 47.0% was from non-household sectors, such as markets, business facilities, and restaurants. The National Waste Statistics Survey is conducted every five years, in which the fifth survey was conducted in 2016–2017, and the sixth survey was conducted in 2021–2022. Results from the sixth survey showed that the composition ratio remained similar to the results of the fifth survey, with vegetables, meat and fish products, and fruits accounting for 28.1, 16.3, and 12.4%, respectively, of total food waste (Figure 3). When examining South Korea's dietary patterns, carbohydrate intake represents 4.3 g per 100 g of food consumed, which is approximately double that of protein and fat. Furthermore, there is minimal variation in carbohydrate consumption throughout the seasons [30]. Koreans primarily base their meals on rice and wheat, and their food culture, characterized by a variety of side dishes, also results in significant vegetable consumption (Figure 3) [31].



(**a**)

Figure 3. Composition ratio and separate discharge rate of food waste: (**a**) composition ratio of food waste (%) and (**b**) separate discharge rate of food waste (%) [31].

The food waste separation rate is an indicator of the proportion of food waste that is collected separately rather than mixed with general waste (Figure 3). Therefore, it reflects the efficacy of the VBWF system. The separate discharge rate of food waste was 88.8%, indicating a decrease of 4.8 percentage units, compared to that in the fifth survey (93.6%). This ratio was calculated using the following equation [31]:

$$\text{The separate discharge rate of food waste} = \left(\frac{\text{Food waste separate discharge amount}}{\text{food waste volume rate mixed discharge amount} + \text{food waste separate discharge amount}}\right)$$

4.2. The Types of Food Waste Recycling Processes

The "recycling of food waste" policy is aimed at utilizing discarded food waste for composting, animal feed, and biogas production. Resource recovery facilities generally adopt the following processes: aerobic composting, wet and dry fermentations for animal feed, and anaerobic digestion for biogas production. The processing stages for each food waste recycling method are shown in Figure 4.

The aerobic composting process involves the fermentation of sorted and ground food waste in a fermentation chamber (Geobox) for 14 days (4 days for feed fermentation). Subsequently, the material is post-fermented for an additional 15 days to mature. Microorganisms, mainly bacteria, decompose organic matter during fermentation. In the subsequent maturation stage, pathogenic microorganisms are eliminated at temperatures exceeding 55 °C, and unpleasant odors are removed [32].

The wet feed-conversion process is a method used by livestock farms, wherein foreign substances such as bone fragments and vinyl are removed from food waste, and the waste is ground while it still contains moisture. Then, the waste is heated to a high temperature of 140 °C for sterilization. The dry feed-conversion process involves placing food waste in a dryer and using high-speed hot air or heating equipment at 390 °C to dry it, until its moisture content is reduced to approximately ≤15%. Thus, it is a straightforward treatment method that consists of sorting by manually selecting foreign materials, drying, and grinding and is commonly carried out on a larger scale in factory-sized facilities [33].

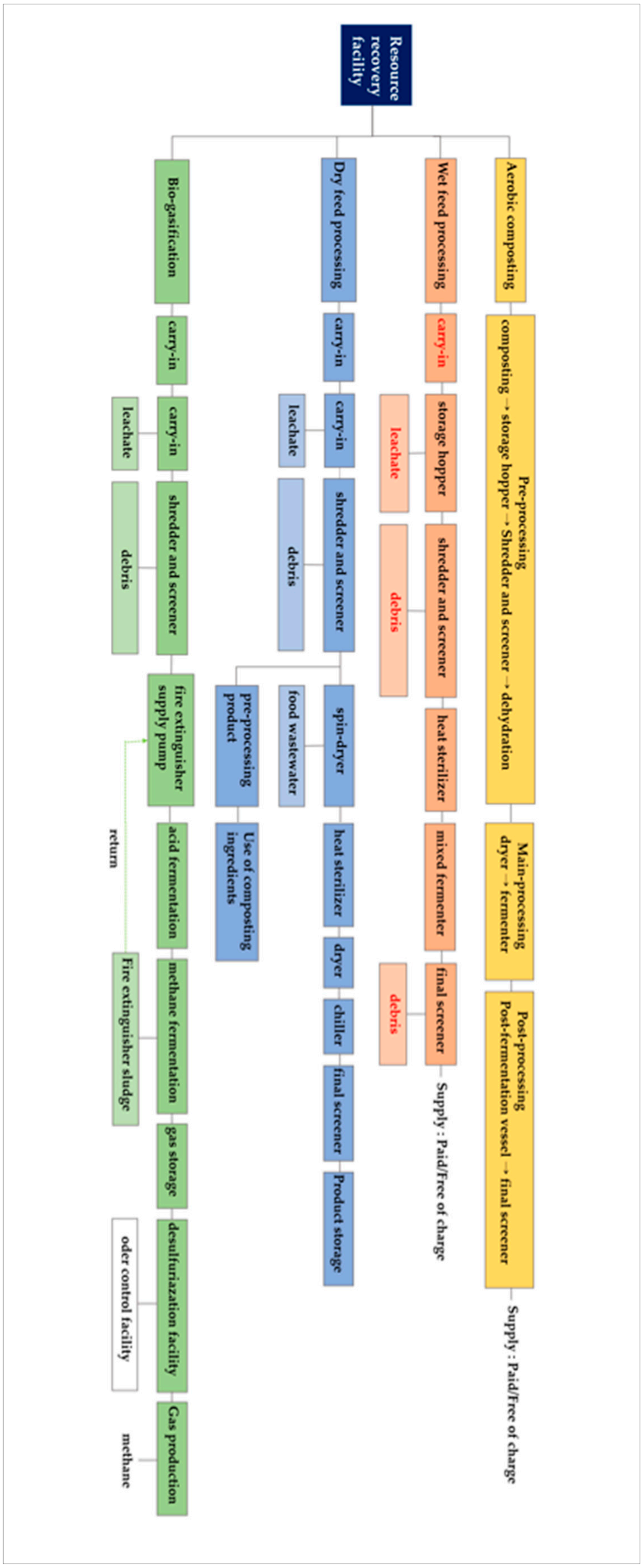


Figure 4. Flowchart of the processes used in different facilities for the recycling of food waste [26].

Facilities Used to Process Food Waste into Animal Feed and Compost

The operation of public waste treatment facilities began with the Optimization Strategy for Waste Treatment Facilities that was implemented in 2011 to address the disparities in waste treatment costs among local governments and establish an integrated management system at the national level [34].

In this study, we conducted regular operational evaluations of the post-management of waste treatment facilities, as stipulated in Articles 55 and 56 of the Waste Management Act. The assessment included the investigations and evaluations of the installation and operational status of the treatment facilities, as well as the evidence for national financial support. The current status of the public resource recovery treatment facilities for feed and compost in the country are presented in Tables 1 and 2, respectively. The methods and utilization rates of feed and compost for public food waste treatment facilities are shown in Table 2. The utilization rates of the feed and compost were calculated using the following formula [35].

$$\text{Usage of feed or compost} = \left\{ \frac{(\text{Paid sales} \times 1.0) + (\text{Provided free of charge and use of self} \times 0.5)}{\text{Production of feed or compost}} \right\} \times 100$$

Table 1. Operational status of public food waste treatment facilities by capacity and resource recovery methods [35].

Categories	Number of Facilities	Distribution of Facilities Based on Capacity	
		>30 Tonnes/Day	<30 Tonnes/Day
Feed	26	25	1
Compost	28	19	9
Others	21	9	12

Table 2. Feed and compost usage methods and usage rates of public food waste treatment facilities [35].

Categories	Number of Productions (Thousand Tonnes/Year)	Method of Usage (Thousand Tonnes/Year)			Usage Rate (%)
		Paid Sales	Provided Free of Charge	Self-Generated and Use [1]	
Feed	67.0	2.8	44.3	-	37.3
Compost	59.4	1.0	57.1	0.003	49.8
Others [2]	115.3	-	55.5	-	24.1

[1.] Food waste generated by households and fed to their animals. [2.] Others: drying, heating, dehydration, and crushing

The public food-waste treatment facilities in the country were analyzed based on the facility capacity. Among the 54 facilities considered in this study, 26 were dedicated to feed conversion, while 28 were dedicated to composting. Among the 54 facilities dedicated to feed conversion and composting, 44 facilities processed $\geq$ 30 tonnes per day while 10 facilities processed < 30 tonnes per day.

Among the different treatment methods considered in this study, the highest utilization rate was observed in composting (49.8%), followed by feed (37.3%), and other methods, such as reduction and organic resource utilization, which had a rate of 24.1%. The total production of compost and feed was 126,400 tonnes per year, with 101,400 tonnes provided free of charge, while 3800 tonnes were sold. The annual assessments and evaluations of the status of waste generation, treatment, and circular utilization provide essential data for resource allocation and utilization planning such as controlling production according to the amount of feed, fertilizer, and biogas resource use, controlling the number of production facilities or companies, and predicting areas in need of resource conversion facilities. Such evaluations are also helpful for establishing basic resource circulation plans and setting national resource circulation goals [36].

4.3. Methods Used to Process Food Waste into Compost, Animal Feed, and Biogas

4.3.1. Compost

During the composting process, the food waste undergoes a series of steps, including sorting and moisture content adjustment at composting facilities. In Korea, food waste primarily comprises rice-based meals with soupy components, leading to a high moisture content of approximately 80–85%. Additionally, the prevalent dietary inclusion of salty fermented foods like kimchi contributes to a salt content of about 3–4%. Consequently, preprocessing becomes necessary due to these elevated levels of moisture and salt content. Furthermore, parameters affecting composting, such as pH and Electrical Conductivity (EC), were found to be notably high [37].

Aerobic composting typically takes about 2 to 3 months, which involves pre-processing, fermentation, and maturation stages. In a mixed fermentation tank, moisture regulation and fermentation agents are added, and the mixture is stirred for 24 h to reduce moisture content to <52%. Following this step in the compost fermentation facility, air is injected for 28 to 30 days while maintaining a temperature of 55 to 60 °C, and the compost is stirred approximately 20 times a day using a compost turner. During the maturation stage, compost is produced by stirring until the moisture content is reduced to <42%. Aerobic composting is the most widely adopted method, because of its relatively low installation costs and easy setup. It has the advantage of a relatively short composting period; however, it requires a large land area for facility installation, along with additives required to regulate the moisture and salt content. In addition, odor-control facilities are necessary for such setups, and the facility operations have significant energy consumption (Table 3) [38,39].

Table 3. Summary of the characteristics of each composting method considered in this study [38].

Category	Principle	Advantage	Disadvantage
Aerobic composting	For a home that carries out composting using aerobic microorganisms, a continuous air supply is required	Short time required for composting	High energy consumption; odors
Anaerobic composting	Food stays for a long time in an enclosed space to decompose; compost and methane gas are produced as by-products	Degree of loss is large	Decomposition is slow
Vermicomposting	Compost production by fermenting food waste and providing it as food for earthworms	Low initial facility investment	Limitation of application in urban areas due to odors

Anaerobic composting involves fermenting food waste with anaerobic and methane-forming microorganisms to produce alcohol and methane, followed by composting the remaining sludge. Anaerobic composting involves utilizing bacteria that function at temperatures of 36 to 38 °C and undergo a fermentation process of about 30 days. Moisture conditions are adjusted to about 60% when preparing raw materials and are maintained at 50 to 55% during the fermentation process after the inoculation of anaerobic microorganisms (Table 3) [40]. Yang et al. [41] indicated that the efficient operation of composting relies on parameters such as pH of 6 to 8, a carbon to nitrogen ratio of 20 to 30:1, 50 to 65% moisture, and a temperature range of 55 to 75 °C. However, these parameters should be adjusted for each composting facility and process.

In addition to conventional aerobic and anaerobic composting methods, vermicomposting has gained attention. Vermicomposting is the utilization of insects and earthworms, to cultivate their excrement, known as vermicompost, for use as fertilizer. Organic waste materials like food scraps serve as excellent food for these organisms, and their excrement enriches the soil [42]. This approach is considered to be an environmentally-friendly resource recycling method and offers the advantage of relatively low installation costs [43]. However, it requires proper environmental control and the maintenance of the temperature, humidity, and pH of the waste, and the installation of facilities for odor removal and leachate treatments (Table 3) [44]. Optimal conditions for vermicomposting include a temperature range of 20 to 30 °C, humidity levels between 60% and 80%, a pH of 7, and a carbon to nitrogen ratio of 15 to 20:1 [45,46].

The quality control of composting materials:

No specific quality standards have yet been established for compost derived from food waste in South Korea. However, the waste composition must follow the specifications for compost under Article 4 of the Fertilizer Management Act [47]. The fertilizer process specification for compost sets the maximum salt content limit at 2.0% [48]. The Fertilizer Management Act regulates the production of compost regardless of whether it is produced from food waste and distributed free of charge or sold for profit. This regulation ensures that the compost production industry is registered and produces compost that meets the standard processing specifications [49].

4.3.2. Animal Feed

The feed processing methods that involve a combination of drying and fermentation offer the advantage of faster processing compared with composting. However, feed processing facilities have the disadvantage of initial high equipment costs and the expenses associated with the maintenance, repair, and overhaul of facilities. Feed processing methods are categorized as wet, dry, or fermentation methods [38,50]. The manufacturing process diagram of wet and dry feed conversion is shown in Figure 5. Wet processing involves the conversion of the feed into a moist form (70 to 80%) [51], whereas dry processing involves drying the feed to remove moisture (≤15%) [51]. The fermentation process employs microbial activity including bacteria such as *Bacillus subtilis*, as well as fungi like *Aspergillus tubingensis* and *Meyerozyma caribbica* to enhance the nutritional quality of the feed [52]. Fermentation can enhance feed digestibility and nutrient content through microbial action but requires the proper control of fermentation conditions. While undergoing the wet fermentation process, there was a 1.24% increase in organic matter, a 7.11% increase in non-fibrous carbohydrates, and a 4.05% increase in nitrogen-free extract [53].

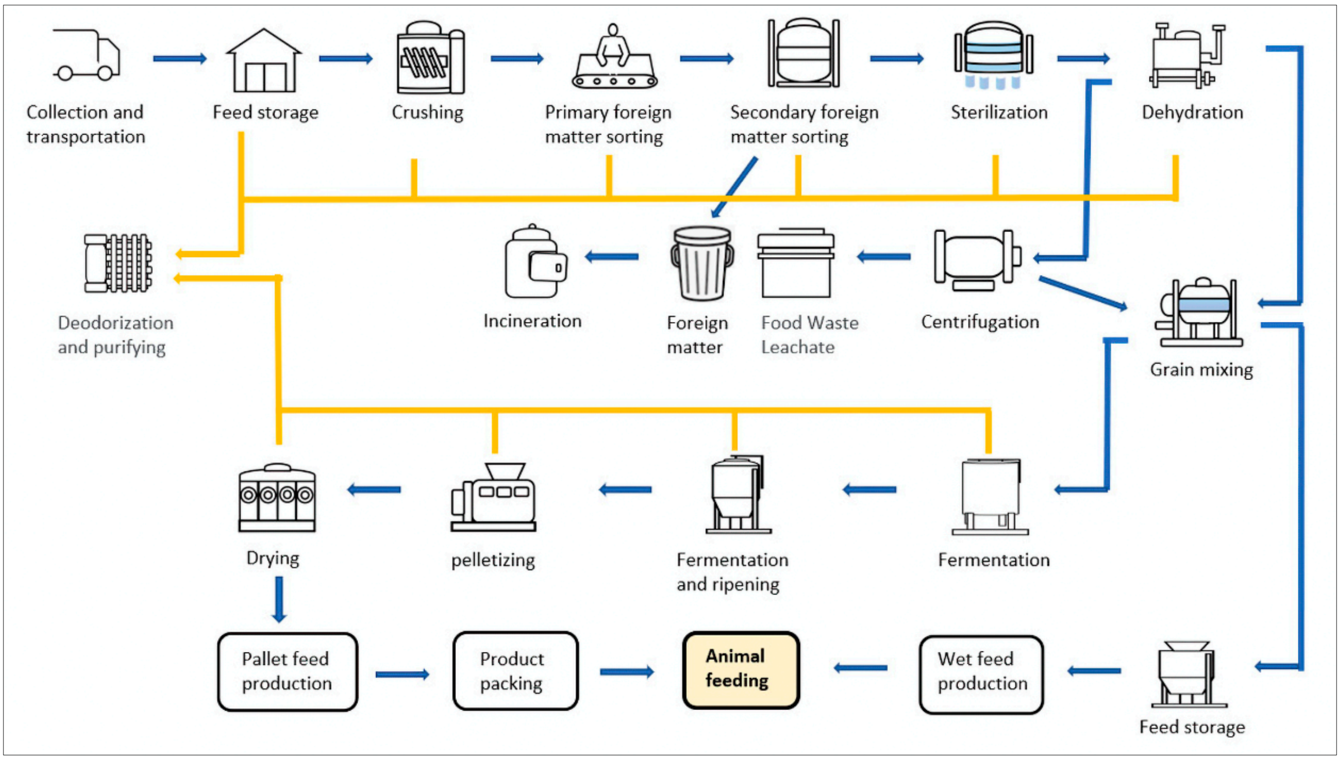


Figure 5. Manufacturing process diagram of wet and dry feed production [54].

Due to the introduction and spread of African Swine Fever in South Korea, the use of leftover food in pig feed has been prohibited since July 2019. As a result, approximately 7.5% (1200 tonnes) of wet feed from the total leftover food waste (15,900 tonnes per day) intended for pig farming is not recycled adequately [55]. In addition to health-related concerns, a range of issues including elevated moisture and salt levels, contamination by foreign materials, unpleasant odors, and the potential for spoilage during transportation and storage have all contributed to the reduced suitability of recycled food waste as a feed ingredient. Due to the prevailing skepticism regarding the quality of recycled food waste, its inclusion as an ingredient in commercial swine diets has proven to be a challenging endeavor [33,56].

However, another approach for using food waste as an animal feed resource involves the use of insects to convert nutrients in food waste to insect meal as animal feed. Novel studies on animal feed technologies that employ black soldier fly larvae have been shown to provide excellent decomposition abilities and subsequently produce high protein and mineral insect meal that can be used as animal feed [57,58]. The utilization of food waste for the cultivation of insects, particularly for applications such as animal feed and other purposes, has garnered significant attention in recent years [59,60]. This increased interest is primarily driven by the perceived environmental and economic advantages associated with this practice, underscoring the increasing inclination towards employing food waste for insect production, which serves diverse objectives, including animal feed, waste mitigation, and sustainable protein generation.

The production of animal feed using plant waste adheres to the criteria and standards for harmful substances. This in turn, aligns with the standards for compound feeds (The Standards and Specifications for Feeds, Ministry of Agriculture, Food and Rural Affairs Notice No. 2022-55). Within the feed standards, the utilization of food waste as animal feed is separately regulated as "other (leftover food feed)". The range and criteria for harmful substances for leftover food feed are specified in Table 4.

Table 4. Ranges and criteria for harmful substances in residual food-waste feed production [61].

Classification	Hazardous Substances	Acceptance Criteria
Management target: heavy metal	Lead (Pb)	20 ppm
	Mercury (Hg)	0.5 ppm
	Cadmium (Cd)	50 ppm
Management target: major mycotoxin	Aflatoxin B1, B2, G1, G2	50 ppb
	Ochratoxin	250 ppb
Management target: minor mycotoxin	Deoxynivalenol (vomitoxin)	10,000 ppb
	Zearalenone	3000 ppb
	Fusarium B1 and B2	60,000 ppb
	T-2/HT-2	500 ppb
Management target: other safety concerns	Free gossypol	1200 ppm
	Cyanide	50 ppm
	Salmonella	Not detected

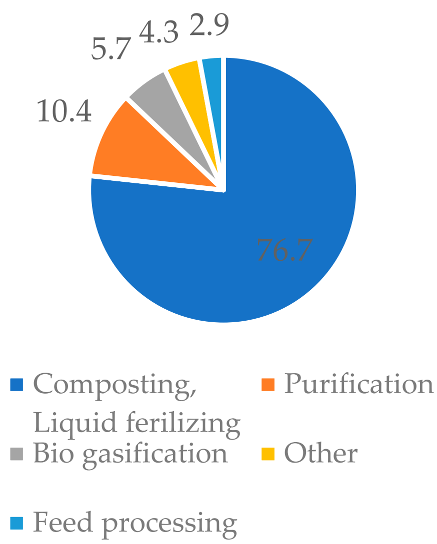
4.3.3. Biogas

Biogas is valuable renewable energy that serves as a secondary source. It is derived from the anaerobic digestion of biodegradable organic materials. Biogas has multiple applications including use as a fuel and as a raw material for the production of chemicals, hydrogen, and gas [62]. Biogas facilities can produce fertilizers and water for agricultural irrigation, while utilizing and controlling organic waste materials, with digestate—a nutrient-rich byproduct of the anaerobic digestion process—serving as an effective fertilizer for soil enrichment in agricultural practices [63,64].

Continual research focuses on various aspects of biogas production and utilization [65], including the optimization of anaerobic digestion by employing mechanical, chemical, and thermodynamic pretreatment processes and providing a solution for handling the organic fraction of municipal solid waste (OFMSW). Schiavon et al. [66] studied the thermal and electrical energy aspects of post biogas production, assessing biogas utilization options and optimizing facility efficiency while considering environmental impacts. Moreover, biogas produced from organic waste sources, such as food waste treatment plants, is supplied to the urban gas pipeline network and used in compressed natural gas vehicles after a sophisticated purification process [67].

In general, there are various types of organic wastes including sewage sludge, livestock manure, food waste, and animal remains which contain a significant amount of energy. They can be processed through anaerobic digestion to generate biogas containing approximately 60% methane and other valuable resources [68]. In 2019, the energy recovery from food waste accounted for 12.5% of total organic waste, while feed production and composting accounted for 36.2% and 38.1%, respectively (Table 5). Over the previous decade, organic waste has increased by 14.7% due to the improvements in Korean living standards. In 2019, the annual generation of organic waste was 65.37 million tonnes. Among the different waste categories, livestock manure accounted for the largest proportion (55.93 million tonnes; 86%). Food waste accounted for 5.22 million tonnes, accounting for 8% of the total organic waste generated in the year (Figure 6) [69]. In terms of organic waste treatment, composting and anaerobic digestion have the highest share, with 50.15 million tonnes (accounting for 76.7% of the total waste treated using such processes). Feed processing accounted for 2.9%, with 1.89 million tonnes being processed annually. Biogas production accounted for 5.7%, with 3.75 million tonnes being generated annually (Table 5). Currently, there are 1341 environmental facilities in South Korea; these include 110 facilities for biogas production that carry out the treatment of waste resources, such as food waste [69].

(**a**)



(**b**)

Figure 6. Organic waste generation and disposal rates of South Korea in 2019: (**a**) organic waste generation rate (%) and (**b**) organic waste disposal rate (%) [69].

Table 5. Utilization ratios of organic waste (unit: million tonnes; %) [69].

Category	Total	Feed Processing	Composting/ Liquid Fertilizing	Bio Gasification	Purification	Others (e.g., Incineration)
Total	65.37 (100)	1.89 (2.9)	50.15 (76.7)	3.75 (5.7)	6.80 (10.4)	2.78 (4.3)
Food waste	5.22 (100)	1.89 (36.2)	1.99 (38.1)	65 (12.5)	-	69 (13.2)
Livestock excretion	55.93 (100)	-	48.16 (86.1)	92 (1.6)	6.80 (12.2)	5 (0.1)
Sewage sludge	4.22 (100)	-	-	2.18 (51.7)	-	2.04 (48.3)

Figure 7 presents the operational status of food waste treatment facilities in 2021, categorized based on the resource utilization method. The operational status of food waste treatment facilities was as follows: composting, anaerobic digestion for biogas production, dry feed production, and wet feed production accounted for 27.7, 14.9, and 47%, respectively. Notably, 0.8% of the privately operated facilities utilized food waste as animal feed [70].

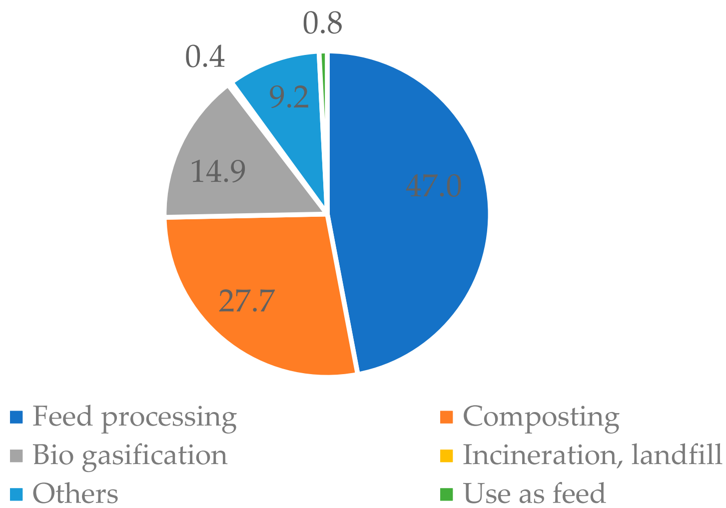


Figure 7. Operational status of food-waste treatment facilities in South Korea in 2021 [70].

Furthermore, according to the data on domestic biogas production and utilization provided by the Ministry of Environment, the year 2020 witnessed the production of 362 million standard cubic meter (Sm^3), of which 302 million Sm^3 was utilized, achieving an overall utilization rate of 83.2%. Among the annual production, 50 million m^3/year (13.8%) was sold as electricity, 38 million m^3/year (10.5%) was used for steam production, 100 million m^3/year (27.6%) was supplied as gas, and 114 million m^3/year (31.4%) was self-consumed. The unused amount amounted to 61 million m^3/year (16.8%), which was fully disposed through combustion [69].

5. Conclusions

South Korea has successfully addressed waste management issues caused by rapid industrialization and urbanization through various recycling policies. However, the emerging issues of resource circulation and environmental preservation that need to be addressed to achieve carbon neutrality present new challenges. The Basic Act on Resource Circulation, enacted in 2016, introduced waste disposal burden fees, along with a performance management system for resource circulation and a certification system to promote resource circulation, to minimize the incineration and landfilling of waste and maximize recycling. To address environmental preservation, South Korea implemented various policies, including the activation of waste separation and collection, resource utilization of food waste, and bio gasification of organic waste. Based on the results and discussion of this study, we propose viable suggestions for utilizing food waste in South Korea.

Although we summarized the situation and challenges of the current resource utilization methods in South Korea, such as anaerobic, aerobic, and insect-based composting, as well as dry and wet fermentation processes for animal feed, and biogas production using categorized materials, there are some limitations that need to be addressed. First, commercial farms that install feed facilities with government subsidies for food waste recycling face difficulties due to the restrictions on feed utilization for the prevention of livestock diseases. Secondly, improvements in processes, such as reducing spoilage during food waste collection and storage, excessive salt content, and odor generation, are necessary to increase nutritional value and ensure safety when upcycling into animal feed. Finally, the bio gasification of organic waste requires technological development to increase productivity and improve resource utilization efficiency.

The efficient utilization of waste resources requires a comprehensive effort, rather than the development of a single technology. We need to optimize methods for handling food waste according to each region's characteristics, emphasizing societal and economic benefits through policies to encourage participation. The continual monitoring of policy effectiveness is essential, alongside crucial technological advancements considering energy and carbon factors. Further research into more detailed waste management methods would aid in fostering sustainable resource circulation tailored to local communities.

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References

1. Jacob-John, J.; D'Souza, C.; Marjoribanks, T.; Singaraju, S.P. Sustainable Development Goals: A review of SDG 12.3 in food supply chain literature. *Benchmarking Int. J.* **2023**, *30*, 3465–3481. [CrossRef]
2. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. The Sixth Assessment Report of the Intergovernmental Panel Climate Change (IPCC). 2021. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf (accessed on 3 October 2023).
3. Climate Change 2021: The Physical Science Basis–IPCC. Available online: https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/ (accessed on 3 October 2023).
4. UNFCCC. A Beginner's Guide to bu Neutrality. 2021. Available online: https://unfccc.int/blog/a-beginner-s-guide-to-climate-neutrality (accessed on 7 September 2023).
5. Tonini, D.; Albizzati, P.F.; Astrup, T.F. Environmental impacts of food waste: Learnings and challenges from a case study on UK. *J. Waste Manag.* **2018**, *76*, 744–766. [CrossRef] [PubMed]
6. Khalid, A.; Arshad, M.; Anjum, M.; Mahmood, T.; Dawson, L. The Anaerobic Digestion of Solid Organic Waste. *J. Waste Manag.* **2011**, *31*, 1737–1744. [CrossRef] [PubMed]
7. Li, Y.; Park, S.Y.; Zhu, J. Solid-State Anaerobic Digestion for Methane Production from Organic Waste. *Renew. Sust. Energ. Rev.* **2011**, *15*, 821–826. [CrossRef]
8. DiGiacomo, A.; Wu, D.; Lenkic, P.; Fraser, B.; Zhao, J.; Kingstone, A. Convenience improves composting and recycling rates in high-density residential buildings. *J. Environ. Plan. Manag.* **2018**, *61*, 309–331. [CrossRef]
9. Shekdar, A.V. Sustainable solid waste management: An integrated approach for Asian countries. *Waste Manag.* **2009**, *29*, 1438–1448. [CrossRef] [PubMed]
10. Sakai, S.; Yoshida, H.; Hirai, Y. International comparative study of 3R and waste management policy developments. *J. Mater. Cycles Waste Manag.* **2011**, *13*, 86–102. [CrossRef]
11. Clercq, D.; Wen, Z.; Gottfried, O.; Schmidt, F.; Fei, F. A review of global strategies promoting the conversion of food waste to bioenergy via anaerobic digestion. *Renew. Sust. Energ. Rev.* **2017**, *79*, 204–221. [CrossRef]

12. Lee, S.; Hur, G.Y. Volume Based Waste Fee (VBWF) System for Municipal Solid Waste. Seoulsolution. 2017. Available online: https://www.seoulsolution.kr/sites/default/files/policy/%ED%99%98%EA%B2%BD_9_p181_Volume%20Based%20Waste%20Fee%20(VBMF)%20System%20for%20Municipal%20Solid%20Waste.pdf (accessed on 3 October 2023).
13. Adelodun, B.; Kim, H.S.; Choi, S.K. Assessment of food waste generation and composition among Korean households using novel sampling and statistical approaches. *Waste Manag.* **2021**, *122*, 71–80. [CrossRef]
14. Korea Land Corporation. Food Waste Composting and Fodder Facility Survey Report. 1998. Available online: https://www.codil.or.kr/filebank/original/RK/OTKLRK010349//OTKLRK010349.pdf?stream=T (accessed on 3 October 2023).
15. Ko, J.Y.; Phae, C.G.; Park, J.S. Effect of Food Waste Direct Landfilling Prohibition on Characteristics of Landfill Gas and Leachate. *Korean Ind. Eng. Chem.* **2007**, *18*, 612–617.
16. Ministry of Environment. Prohibition of Direct Landfilling of Food Waste Since 2005. Available online: https://me.go.kr/home/web/policy_data/read.do;jsessionid=amcz5G0ZkFShk-owLWheYPEO.mehome1?pagerOffset=4370&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=92&orgCd=&condition.deleteYn=N&seq=1939 (accessed on 3 October 2023).
17. Yoo, Y.K. Seoul Waste Management Policy, Seoul Archive. 2015. Available online: https://seoulsolution.kr/ko/content/3028 (accessed on 18 September 2023).
18. Kim, I.G.; Kwon, P.S.; Kang, G.M.; Kim, O.S.; Choi, Y.K. 50 years of Korean environment. Korea Environmental Technology Research Institute. 1996. Available online: http://repository.kei.re.kr/handle/2017.oak/18886 (accessed on 7 September 2023).
19. Cho, O.B. Waste Treatment and Management. National Archives of Korea. 2006. Available online: https://www.archives.go.kr/next/newsearch/listSubjectDescription.do?id=003876&sitePage= (accessed on 7 September 2023).
20. National Law Information Center. The Filth Cleaning Act. Law No. 914 Enacted on 30 December 1961. Available online: https://www.law.go.kr/LSW/lsInfoP.do?lsiSeq=455#0000 (accessed on 7 September 2023).
21. National Law Information Center. The Filth Cleaning Act Law No. 2584 Enacted on 9 March 1973. Available online: https://glaw.scourt.go.kr/wsjo/lawod/sjo192.do?lawodNm=%EC%98%A4%EB%AC%BC%EC%B2%AD%EC%86%8C%EB%B2%95&jomunNo=20&jomunGajiNo= (accessed on 4 January 2024).
22. Lee, H.S. Major Air Conservation Policy Initiatives and Future Directions. Ministry of Economy and Finance and Korea Research Institute for Human Settlements. 1997. Available online: https://www.hri.co.kr/upload/board/HER199703_02.PDF (accessed on 10 September 2023).
23. National Law Information Center. The Environmental Conservation Act Enforcement Regulations [Appendix 3], Revised on 7 January 1981. Available online: https://www.law.go.kr/LSW/lsInfoP.do?lsiSeq=48948#J13624147 (accessed on 7 September 2023).
24. Kim, J.D.; Kim, D.K.; Lee, H.K. The Story of the Ministry of Environment through Records. Ministry of Environment. 2015. Available online: http://www.me.go.kr/home/web/board/read.do?pagerOffset=10&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=10181&orgCd=&boardMasterId=54&boardCategoryId=&boardId=502230&decorator= (accessed on 10 September 2023).
25. Korea Institute for Health and Social Affairs. Measures for Cultivating Improved Dietary Habits. 1998. Available online: http://repository.kihasa.re.kr/bitstream/201002/1183/1/%EC%A0%95%EC%B1%85%EB%B3%B4%EA%B3%A0%EC%84%9C%201998-09.pdf (accessed on 10 September 2023).
26. Ministry of Environment. Food Waste Reduction and Recycling, Achievements and Future. 2017. Available online: https://school.jbedu.kr/_cmm/fileDownload/puan-m/M01030402/bb4f827b39ae849d7d7747a8ba0b31fe (accessed on 3 October 2023).
27. Ministry of Environment. 1st Basic Plan of Resource Circulation in South Korea (2018–2027). 2018. Available online: http://www.me.go.kr/home/web/policy_data/read.do?menuId=10265&seq=7193 (accessed on 3 October 2023).
28. National Law Information Center. Promotion of Biogas Production and Utilization from Organic Waste Resources (Notice No. 19151). 2022b. Available online: https://www.law.go.kr/%EB%B2%95%EB%A0%B9/%EC%9C%A0%EA%B8%B0%EC%84%B1%ED%8F%90%EC%9E%90%EC%9B%90%EC%9D%84%ED%99%9C%EC%9A%A9%ED%95%9C%EB%B0%94%EC%9D%B4%EC%98%A4%EA%B0%80%EC%8A%A4%EC%9D%98%EC%83%9D%EC%82%B0%EB%B0%8F%EC%9D%B4%EC%9A%A9%EC%B4%89%EC%A7%84%EB%B2%95/(19151,20221230) (accessed on 3 October 2023).
29. Ministry of Environmental and Korea Environmental Corporation. National Waste Generation and Disposal Status. 2014–2019. Available online: https://www.recycling-info.or.kr/rrs/stat/envStatList.do?menuNo=M13020201 (accessed on 10 September 2023).
30. Lee, J.D.; Yoon, M.Y.; Choi, W.I.; Bae, S.J.; Seo, C.D. Effect of seasonal variations of organic loading rate and acid phase on methane yield of food waste leachate in South Korea. *Appl. Biol. Chem.* **2017**, *60*, 87–93. [CrossRef]
31. Korean Resource recirculation Information System. The 6th National Waste Statistics Survey (2021~2022). 2022. Available online: https://www.recycling-info.or.kr/rrs/stat/envStatDetail.do;jsessionid=xfpHnAidOc6ytjXQc6EKwYIE7rHdjXFtRtDm0ElispUHas8gxZM8z6YBvIs8B8lB.RCIS-WAS_servlet_engine1?bbsId=BBSMSTR_000000000002&nttId=1331&s_nttSj=KEC011 (accessed on 10 September 2023).
32. Nongsaro. Organic Compost Manufacturing Technology. 2017. Available online: https://www.nongsaro.go.kr/portal/ps/psz/psza/contentSub.ps?menuId=PS04185&cntntsNo=207210 (accessed on 25 September 2023).

33. Kim, H.J. Efficient Food Waste Treatment Plan. Incheon Green Environment Support Center. 2020. Available online: https://igec.re.kr/r_b_year/%EC%9D%8C%EC%8B%9D%EB%AC%BC%EC%93%B0%EB%A0%88%EA%B8%B0%EC%9D%98-%ED%9A%A8%EC%9C%A8%EC%A0%81-%EC%B2%98%EB%A6%AC-%EB%B0%A9%EC%95%88/?sca=%EC%A0%95%EC%B1%85&page=9 (accessed on 18 September 2023).
34. Ministry of Environment. 2015 Waste Treatment Business and Waste Treatment Facility Installation and Operation Status Evaluation Result Report. 2016. Available online: http://www.me.go.kr/home/web/policy_data/read.do?pagerOffset=23&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=10259&orgCd=&condition.orderSeqId=6843&condition.rnSeq=749&condition.deleteYn=N&seq=6845 (accessed on 15 September 2023).
35. Ministry of Environment. 2022 Waste Treatment Business and Waste Treatment Facility Installation and Operation Status Evaluation Result Report. 2023. Available online: http://www.me.go.kr/home/web/policy_data/read.do?menuId=10265&seq=8016 (accessed on 7 September 2023).
36. Ministry of Environmental and Korea Environmental Corporation. National Waste Generation and Disposal Status. 2021. Available online: https://www.recycling-info.or.kr/rrs/stat/envStatDetail.do?menuNo=M13020201&pageIndex=1&bbsId=BBSMSTR_000000000002&s_nttSj=KEC005&nttId=1296&searchBgnDe=&searchEndDe= (accessed on 7 September 2023).
37. Lee, J.H.; Yeom, K.R.; Yang, J.W.; Choi, Y.J.; Hwang, H.C.; Jeon, Y.J.; Lee, C.H.; Choi, B.S.; Oh, T.K.; Park, S.J. Comparing the composting characteristics of food waste supplemented with various bulking agents. *Korean J. Agric. Sci.* **2019**, *46*, 897–905. [CrossRef]
38. Korea Institute of Science and Technology Information. Food Waste Composting. 2002. Available online: https://scienceon.kisti.re.kr/commons/util/originalView.do?dbt=TRKO&cn=TRKO201000015694 (accessed on 21 September 2023).
39. Jong, D.H. Activation Plan for the Use of Food Compost in Daejeon. Daejeon Development Institute. 2013. Available online: https://www.dsi.re.kr/board.es?mid=a10101000000&bid=0001&act=view&list_no=3104&nPage=79&sel_date= (accessed on 21 September 2023).
40. Yun, R.J. Fertilization by Anaerobic Bacteria in Plant Growth. Korea Institute of Science and Technology. 2004. Available online: https://www.reseat.or.kr/portal/bbs/B0000261/view.do?nttId=159550&menuNo=200019&pageIndex=6028 (accessed on 18 September 2023).
41. Yang, S.I.; Ji, K.M.; Jeon, H.B. A Review on Efficient Operation Technology of Compost Depot). *Clean Technol.* **2017**, *23*, 345–356.
42. Domínguez, J. State of the art and new perspectives on vermicomposting research. In *Earthworm Ecology*, 2nd ed.; Edwards, C.A., Ed.; CRC Press LLC.: Boca Raton, FL, USA, 2004; pp. 401–424.
43. Enebe, M.C.; Erasmus, M. Vermicomposting technology—A perspective on vermicompost production technologies, limitations and prospects. *J. Environ. Manag.* **2023**, *345*, 118585. [CrossRef] [PubMed]
44. Wu, L.; Ma, L.W.; Martinez, G.A. Comparison of methods for evaluating stability and maturity of biosolids compost. *J. Environ. Qual.* **2000**, *29*, 424–429. [CrossRef]
45. Rupani, P.F.; Alkarkhi, A.F.M.; Shahadat, M.; Embrandiri, A.; El-Mesery, H.S.; Wang, H.; Shao, W. Bio-Optimization of Chemical Parameters and Earthworm Biomass for Efficient Vermicomposting of Different Palm Oil Mill Waste Mixtures. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2092. [CrossRef]
46. Othman, N.; Irwan, J.M.; Roslan, M.A. Vermicomposting of Food Waste. *Int. J. Integr. Eng.* **2012**, *4*, 39–48.
47. National Law Information Center. Article 4 of the Fertilizer Management Act. 2013. Available online: https://www.law.go.kr/%EB%B2%95%EB%A0%B9/%EB%B9%84%EB%A3%8C%EA%B4%80%EB%A6%AC%EB%B2%95 (accessed on 16 September 2023).
48. Rural Development Administration. Opening the Way to Industrialize Food Waste Disposal Using 'Black Solider Fly'. 2018. Available online: http://www.rda.go.kr/board/board.do?mode=view&prgId=day_farmprmninfoEntry&dataNo=100000744772 (accessed on 16 September 2023).
49. National Law Information Center. Article 11 of the Feed Management Act. 2022a. Available online: https://www.law.go.kr/lsSc.do?section=&menuId=1&subMenuId=15&tabMenuId=81&eventGubun=060101&query=%EC%82%AC%EB%A3%8C%EA%B4%80%EB%A6%AC%EB%B2%95+%EC%A0%9C+11%EC%A1%B0(%EC%82%AC%EB%A3%8C%EC%9D%98+%EA%B3%B5%EC%A0%95+%EB%93%B1)2020.3.24+%ED%83%80%EB%B2%95%EA%B0%9C%EC%A0%95#J11:0 (accessed on 16 September 2023).
50. Manuel, C.R.; Carlos, Q.F.; Carmen, P.C.; Marisela, V.D.; Iván, M.A. Fungal solid-state fermentation of food waste for biohydrogen production by dark fermentation. *Int. J. Hydrogen Energy* **2022**, *47*, 30062–30073. [CrossRef]
51. Rasool, K.; Hussain, S.; Shahzad, A. Comprehensive insights into sustainable conversion of agricultural and food waste into microbial protein for animal feed production. *Rev. Environ. Sci. Biotechnol.* **2023**, *22*, 527–562. [CrossRef]
52. Saleh, A.A.; Shukry, M.; Farrag, F.; Soliman, M.M.; Abdel-Moneim, A.E. Effect of Feeding Wet Feed or Wet Feed Fermented by Bacillus licheniformis on Growth Performance, Histopathology and Growth and Lipid Metabolism Marker Genes in Broiler Chickens. *Animals* **2021**, *11*, 83. [CrossRef]
53. Jee, S.K.; Baik, H.Y.; Kwak, S.W. Evaluation on Feed-Nutritional Change of Food Waste According to Different Processing Methods and Trouble-shooting Strategy. *J. Anim. Sci. Technol.* **2005**, *47*, 513–524.
54. Korea Waste Association. Manufacturing Process Diagram of Wet and Dry Feed Production. Available online: http://www.kwaste.or.kr/bbs/content.php?co_id=sub040205(kwaste.or.kr) (accessed on 12 July 2023).

55. Bu, A.S. Let's Realize Carbon Negative by Turning Leftover Food into Resources. Korea Food Logistics Waste Collection and Transportation Industry Association. 2021. Available online: https://m.ecomedia.co.kr/news/newsview.php?ncode=1065579852072175 (accessed on 28 September 2023).
56. Park, G.L.; Yun, S.M.; Ju, S.W.; Long, F.H.; Park, Y.H.; Kim, Y.Y. Effects of Fermented Food Waste Supplementation on Growth Performance and Pork Quality in Pig. *J. Anim. Sci. Technol.* **2006**, *48*, 361–374.
57. Park, H.K.; Choi, C.Y.; Nam, H.S.; Kim, H.S.; Kim, Y.S.; Ma, J.Y.; No, K.S. Nutritional value of black soldier fly, Hermetia illucens (Diptera: Stratiomyidae) as a feed supplement for fish. *J. Seric. Entomol. Sci.* **2013**, *51*, 95–98. [CrossRef]
58. Lee, S.Y.; Kim, Y.J. Removal Efficiency of Organic Waste Resources using Black Soldier Fly. *J. Korea Soc. Waste Manag.* **2015**, *32*, 276–280. [CrossRef]
59. Oonincx, D.G.A.B.; van Itterbeeck, J.; Heetkamp, M.J.W.; van den Brand, H.; van Loon, J.J.A.; van Huis, A. An Exploration on Greenhouse Gas and Ammonia Production by Insect Species Suitable for Animal or Human Consumption. *PLoS ONE* **2010**, *5*, e14445. [CrossRef] [PubMed]
60. Diener, S.; Studt Solano, N.M.; Roa Gutiérrez, F. Biological Treatment of Municipal Organic Waste using Black Soldier Fly Larvae. *Waste Biomass Valor* **2011**, *2*, 357–363. [CrossRef]
61. Rural Development Administration. Establishment and Designation of Fertilizer Process Standards (Full Revision). 2019. Available online: https://www.rda.go.kr/board/board.do?ccatgId=&menu_id=ofc&boardId=rdalw&searchKey=&userJumin=&searchVal=&searchSDate=&prgId=law_rdalwEntry&portlet_kind=default&portlet_rowCnt=4&mode=view&portlet_gubun=1&currPage=1&CONTENT2=&searchEDate=&CONTENT1=&nckUserNm=&list_kind=news&CONTENT3=&dataNo=100000753723&CONTENT5=&menu_nm=%C7%E0%C1%A4%C1%A4%BA%B8 (accessed on 16 September 2023).
62. Awe, O.W.; Zhao, Y.; Nzihou, A.; Minh, D.P.; Lyczko, N. A Review of Biogas Utilisation, Purification and Upgrading Technologies: Review. *Waste Biomass Valori* **2017**, *8*, 267–283. [CrossRef]
63. Otun, T.F.; Ojo, O.M.; Ajibade, F.O.; Babatola, J.O. Evaluation of biogas production from the digestion and co-digestion of animal waste, food waste and fruit waste. *Int. J. Environ.* **2015**, *3*, 12–24.
64. Przygocka-Cyna, K.; Grzebisz, W. Biogas digestate–benefits and risks for soil fertility and crop quality–an evaluation of grain maize response. *Open Chem.* **2018**, *16*, 258–271. [CrossRef]
65. Andreottola, G.; Ragazzi, M.; Foladori, P.; Villa, R.; Langone, M.; Rada, E.C. The unit intregrated approch for OFMSW Treatment. *Univ. Politeh. Buchar. Sci. Bull.* **2012**, *74*, 19–26.
66. Schiavon, M.; Rada, E.C.; Cioca, L.; Torrett, V. Environmental and managerial advantages of treatment plants exploiting biogas from food waste. *J. Energy Prod. Mgmt.* **2018**, *3*, 292–306. [CrossRef]
67. Park, J.H.; Kang, Y.J. Biofuel. Korea Institute of S&T Evaluation and Planning. 2022. Available online: https://www.kistep.re.kr/board.es?mid=a10306010000&bid=0031&list_no=42590&act=view (accessed on 10 September 2023).
68. Ministry of Environment. Policy Direction for Bio Gasification of Organic Waste Resources. 2022. Available online: https://me.go.kr/home/web/policy_data/read.do?pagerOffset=0&maxPageItems=10&maxIndexPages=10&searchKey=title&searchValue=%ED%8F%90%EC%9E%90%EC%9B%90&menuId=10259&orgCd=&condition.toInpYmd=null&condition.fromInpYmd=null&condition.deleteYn=N&condition.deptNm=null&seq=7923 (accessed on 10 September 2023).
69. Ministry of Environment. Status of Organic Waste Bio Gasification Facilities. 2020. Available online: http://www.me.go.kr/home/web/policy_data/read.do?pagerOffset=0&maxPageItems=10&maxIndexPages=10&searchKey=title&searchValue=%EC%9C%A0%EA%B8%B0%EC%84%B1%ED%8F%90%EC%9E%90%EC%9B%90+%EB%B0%94%EC%9D%B4%EC%98%A4%EA%B0%80%EC%8A%A4%ED%99%94%EC%8B%9C%EC%84%A4+%ED%98%84%ED%99%A9&menuId=10263&orgCd=&condition.toInpYmd=null&condition.fromInpYmd=null&condition.deleteYn=N&condition.deptNm=null&seq=7683 (accessed on 10 September 2023).
70. Ministry of Environment. Operation Status of Food Waste Handling Facilities. 2021. Available online: https://me.go.kr/home/web/policy_data/read.do;jsessionid=9F0ba0rkxccsS0qlFLpGLhhj.mehome1?pagerOffset=30&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=10259&orgCd=&condition.toInpYmd=null&condition.fromInpYmd=null&condition.deleteYn=N&condition.deptNm=null&seq=7916 (accessed on 10 September 2023).