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Development of a System Suitable for an Apartment Complex for the Collective Recovery of Solid Resources from Food Waste: A Study on South Korea

Yong-Woo Jeon

Environmental Technology Division, Korea Testing Laboratory, Seoul 08389, Republic of Korea; ywjeon@gmail.com

Abstract: The installation of food waste disposers has been prohibited in South Korea, due to conflicts with governmental policies that are focused on resource recovery from food waste and concerns about potential damage to the city's sewer system. However, there is a growing demand for such systems in the country. This study proposes a system for the collective recovery of solid resources from food waste tailored for apartment complexes in South Korea, using an innovative solid–liquid separation technology. In the pilot experiment, 49.60% of the solids fed into the system were recovered as solid matter, confirming its practical applicability. Ultimately, a solid resource collective recovery system suitable for the high-rise apartment residence style of South Korea was developed and applied to an actual apartment complex. The final-stage solids were discharged from the system and processed through bio-drying, subsequently exhibiting a combustible material content of 67.06%, higher heating value (HHV) of 4843 kcal/kg, and lower heating value (LHV) of 3759 kcal/kg; moreover, they have the potential to be repurposed as biomass–solid refuse fuel (bio-SFR), compost, feed, and substrate for biogas production. The proposed food waste disposal system not only aligns with governmental policies, but also facilitates the recovery of high-quality resources from food waste, while providing a sustainable waste management solution.

Keywords: food waste; disposer; solid recovery; solid–liquid separation; bio-drying

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1. Introduction

The daily amount of food waste generated in South Korea in 2021 was approximately 14,000 tons, amounting to 30% of the total domestic waste that year, indicating the highest proportion among all the domestic waste types; this amount is steadily increasing annually [1]. This figure is notably higher than that of the United States of America (USA) (with the food waste amounting to 10% of the country's total domestic waste). Since 1995 (when statistics records were initiated), South Korea's food waste recycling rate has shown a consistent upward trend, peaking at 96.0% in 2012 and gradually declining to 88.2% as of 2021 (Figure 1).

Food waste generation in South Korea portrays an increasing trend, with a significant surge from 2013 onward, reaching a peak of 16,379 tons per day in 2018 before decreasing to 13,696 tons per day in 2021. This decrease coincides with the period of the COVID-19 pandemic; it should be noted that even though the pandemic may have contributed to the decline in food waste, various studies indicate different correlation results. Previous reports on South Korea indicate an increase in the food waste generated at the household-level due to the pandemic [2,3]. This study focuses on the recent surge in food waste disposer installations in households as a potential cause for the recent downturn in the food waste generation statistics of the country.

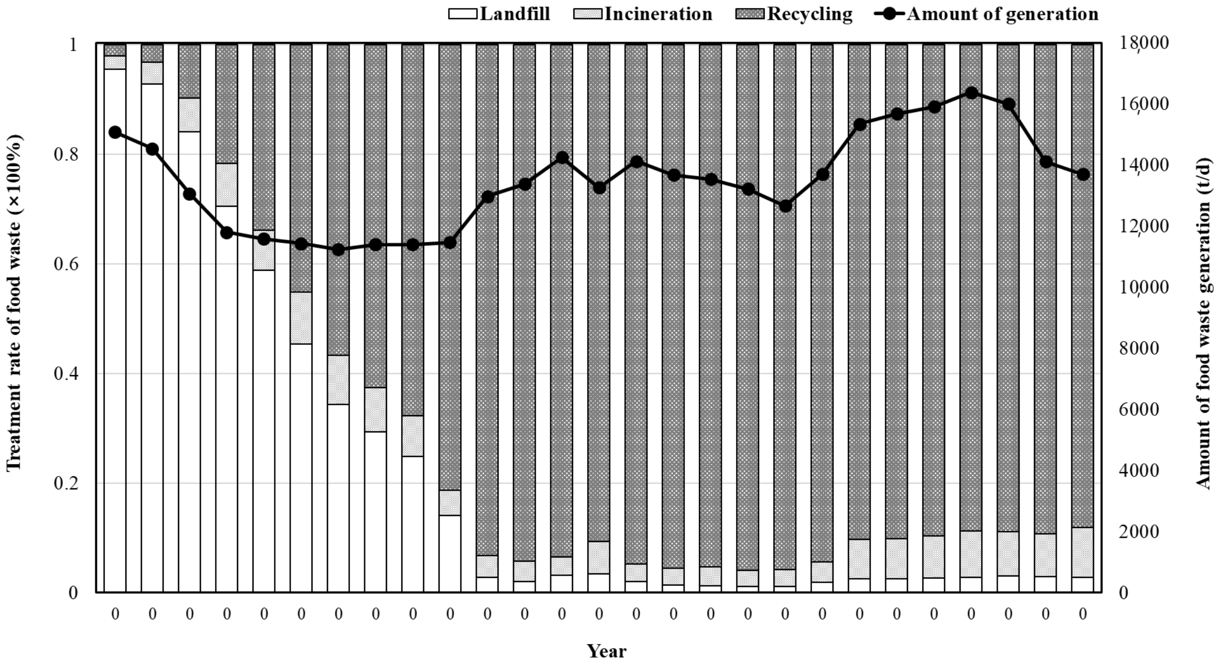

Figure 1. Status of food waste generation and treatment in South Korea for 1995–2021.

The food waste disposer, invented by John W. Hammes in 1927 in the USA, grinds kitchen waste for disposal into the sewer [4]. It offers a hygienic and convenient solution for residential food waste management by swiftly processing food waste, preventing unpleasant odors caused by improper storage, and obviating the need for separate collection containers or bags [5]. However, concerns have since been raised regarding the increased pollutant loads in sewer systems, as well as soil and groundwater contamination in areas that lack well-maintained sewer systems. Different issues, such as sewage flow obstruction due to the deposition of shredded food waste and the odor from decomposed food particles, compound these concerns. Consequently, the use of food waste disposers is currently prohibited in South Korea [6].

Despite the rise in food waste generation in the country since 2013, the recycling rate of food waste has decreased. This decline can be attributed to the inability of South Korea's food waste recycling facilities to cope with the rapid surge in food waste generation, alongside the prohibition on feed production from food waste recycling facilities, following the outbreak of African Swine Fever (ASF) in South Korea in 2019 [7].

At present, the majority of food waste generated in the country is converted into compost, feed, or biogas in recycling facilities. The recycling rate depicted in Figure 1 denotes the proportion of food waste treated in recycling facilities. Korean food waste recycling facilities typically possess treatment capacities that range from tens to hundreds of tons per day. However, numerous challenges persist, including the costs and inconvenience associated with the separation and collection of food waste, mandatory removal of foreign materials, degradation of recycled product quality due to the presence of salts in food waste, and the generation of highly concentrated odors and wastewater during the recycling process [4,6].

As of 2022, apartment housing in South Korea constitutes 64.0% of the total housing in the country (with a 0.5 percentage point increase compared to that of the previous year), with households residing in apartments accounting for 52.4% (a 0.4 percentage point increase compared to the previous year), indicating a significant concentration of residences in high-rise structures [8]. Furthermore, the population of individuals aged 65 and above is steadily increasing each year. Given the current status of South Korea, the existing policy of collecting and transporting food waste to recycling facilities poses a considerable inconvenience to the residents.

Despite the ongoing discussions regarding the distribution of food waste disposers as a result of the above-mentioned situation in the country, particularly those within academia and local governments, the formal introduction of disposers has yet to materialize, due to the perceived conflicts with the national waste resource recovery policy, resulting only in one-time pilot projects. Conventional disposers shred food waste finely and discharge it into the sewer system along with kitchen wastewater, which conflicts with the South Korean government's policy advocating for the recycling of food waste as a resource. In South Korea, research and pilot initiatives for the distribution of food waste disposer systems focus on the treatment type before discharging the waste into the sewer system. This method entails the passage of ground food waste and kitchen wastewater through a wastewater treatment system, where it is treated before being discharged into the sewers, to mitigate the pollutant load in the public sewer system. However, this approach is hampered by high facility and treatment costs and still fundamentally conflicts with the food waste recycling policy of the Korea Ministry of Environment [6].

In this study, we propose a novel food waste disposer system that integrates a solid recovery process. This system segregates the solids and liquid from shredded food waste, retrieving only the solid material while discharging the wastewater into the sewer, with a solid discharge rate of less than 20% (thus meeting the legal standard of South Korea). By recovering the solids before discharging into the sewer, the system can help prevent issues such as pipeline obstruction due to the deposition of shredded waste and increased load on sewage treatment facilities. Furthermore, the recovered solids, devoid of contamination and foreign materials, are more readily recyclable than conventionally collected food waste. This study evaluates the performance of the solid recovery system and the quality of discharged water through pilot experiments, while simulating the actual discharge conditions of food waste disposers. Subsequently, the feasibility of the designed system was assessed through long-term continuous operation. Ultimately, a solid-resource collective recovery system tailored to the high-rise apartment residence style of South Korea was developed and implemented in an actual apartment complex. The final solids discharged from our system, having undergone the bio-drying process, were assessed for their suitability as feed, compost, biomass–solid refuse fuel (bio-SFR), and biogas substrate.

Widespread distribution of the developed system among high-rise apartments in South Korea can enhance the convenience of food waste separation for residents and mitigate the distortions in the figures related to food waste generation in Korea (Figure 1). Moreover, our model may potentially reverse the declining trend in the recycling rate of food waste in the country observed since 2013.

2. Materials and Methods

2.1. Experimental Equipment

2.1.1. Food Waste Disposer Coupled with Solid Recovery Process: A Pilot-Scale Experiment

The pilot experimental system was devised to enable the recovery of solids from a mixture of food waste and effluent water that had been ground by a food waste disposer. Figure 2 illustrates the layout of the pilot experimental system used in this study, comprising a food waste disposer, storage and service tank, solid–liquid separation unit, and solid and liquid collectors that are connected sequentially. The disposer (HYENA, Seoul, South Korea) utilized in the model features a hammer mill and cutter (for providing dual-grind capability to the disposer), along with an impeller structure with a forced transport function to mitigate the deposition of ground food waste and subsequent plumbing blockages. Additionally, to conserve water during the grinding process, the model includes a separate container for storing the wastewater generated during cooking and dishwashing, thereby distinguishing the model from other disposers.

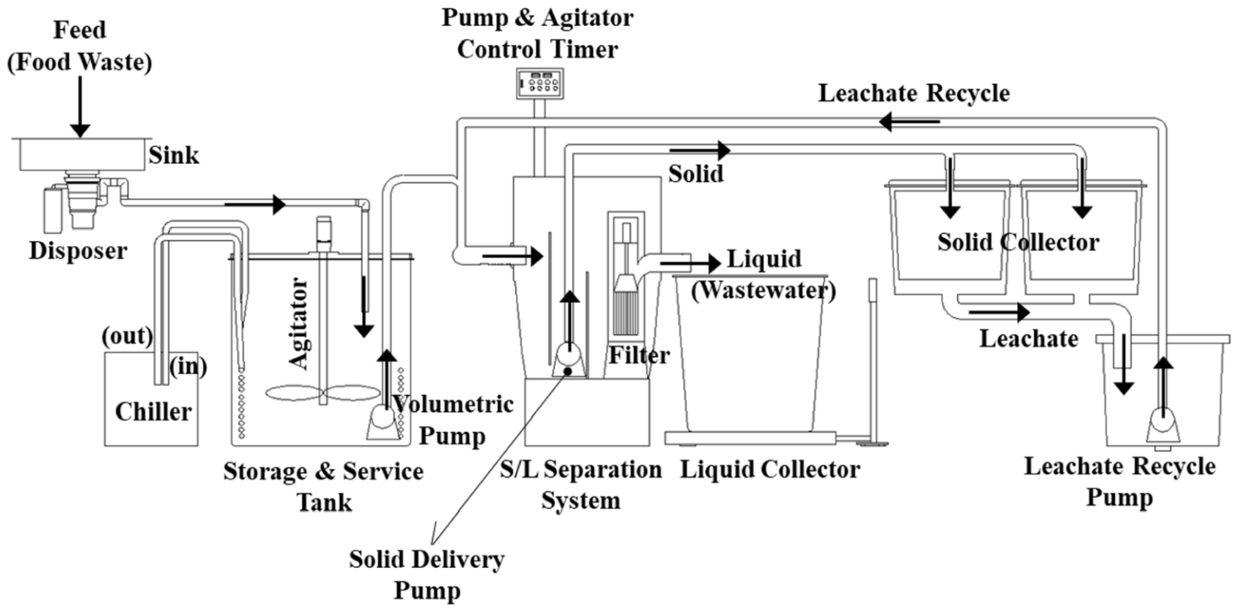

Figure 2. The schematic diagram of the pilot experimental system coupled food waste disposer with solid recovery process.

The solid–liquid (S/L) separation unit, positioned downstream of the disposer, facilitated the efficient separation of solid and liquid materials from the ground food waste. It was designed to channel solid materials to a solid collector, using a solid delivery pump, while allowing liquid (wastewater) to permeate through an internal filter and be discharged into the liquid collector. To streamline the long-term experiment, storage and service tanks (one of each) were interposed between the disposer and the S/L separation unit. The ground materials from the disposer were automatically supplied (in a designated quantity) to the S/L separation unit, using a volumetric pump. With a total capacity of 500 L, the storage and service tank could store an amount of ground materials (equivalent to the amount generated in two days) from the disposer. To minimize decomposition and degradation during storage and feeding, a chiller was installed to maintain the tank's internal temperature, and the pump and agitator were operated only during feeding (controlled by a timer). The solid recovery device employed in the system had a basket-like shape, with a mesh to filter out solids. The mesh size was set to 1.0 mm based on preliminary studies of S/L separation of ground mixture that used mesh sizes of 0.75–1.5 mm.

2.1.2. Full-Scale System Suitable for an Apartment Complex for the Collective Recovery of Solid Resources from Food Waste

The pilot study achieved the target solid recovery performance while meeting the legal standards imposed in South Korea. Subsequently, the system was expanded and refined to improve user convenience, leading to the development and implementation of a full-scale system. The finalized recovery system developed through this study included vertical and horizontal drainpipes, along with a food waste disposer, resource-recovery device installed in the basement floors of multi-unit housing, and an integrated control device. The resource-recovery device would separate the solids from the liquid after food waste had been generated from each household. Then, the device would recover the solids through the bio-drying process and discharge the wastewater into the sewer, with a solid discharge rate of less than 20% (Figure 3).

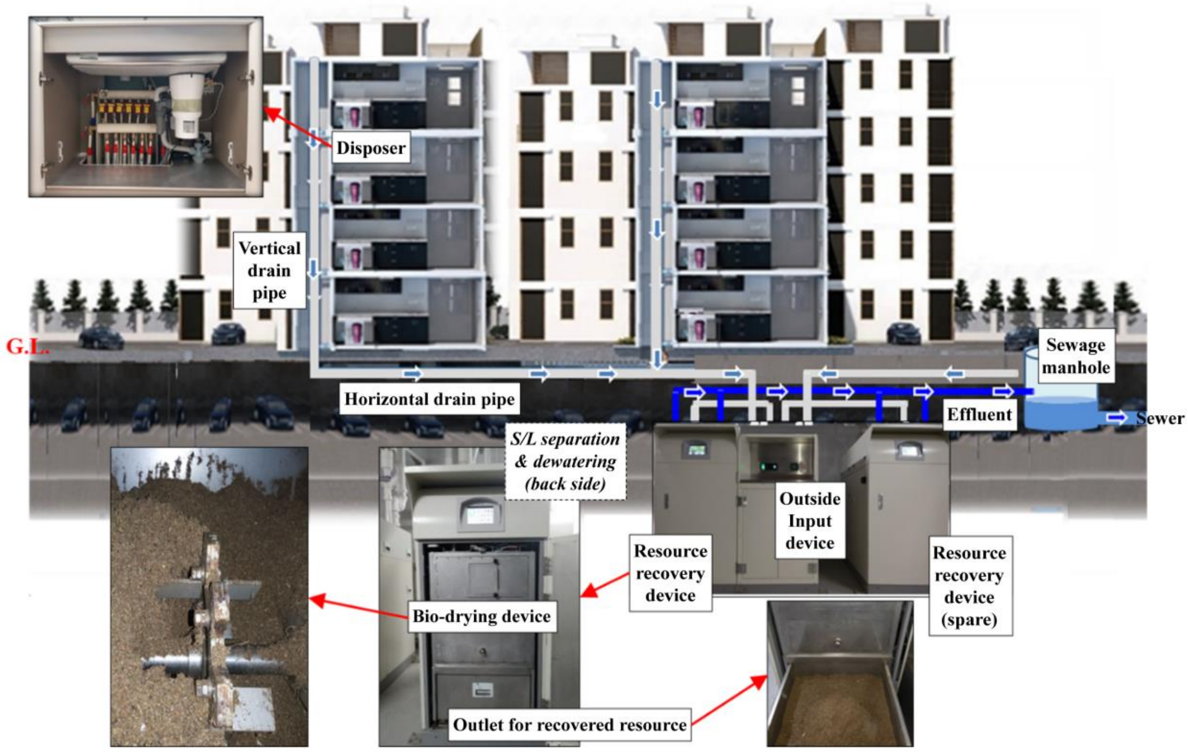

Figure 3. Illustration of the full-scale system suitable for an apartment complex for the collective recovery of solid resources from food waste.

The recovered solids underwent bio-drying and were finally discharged in the form of dried matter. Bio-drying, a concept similar to composting, is aimed at removing or reducing water from biodegradable waste with high water content [9]. The process uses the heat released during the decomposition of biodegradable waste to reduce the moisture content of the waste and partially stabilize the waste matter. The removal or reduction of moisture using the bio-drying process involves the evaporation of liquid water through the aerobic decomposition of the organic material or the reduction in water vapor via aeration [10]. In addition, bio-drying has the advantage of a short retention time and high-quality solid fuel production [11]. The bio-drying device designed for the full-scale system was a U-shaped horizontal cylinder reactor with a flat top, and the internal effective volume was 0.8 m^3. Additionally, a transparent window for observing the internal state and a K-type thermocouple for monitoring internal temperature were installed.

This full-scale system was installed in September 2021 in a total of 1446 households spread over nine buildings located in Seoul, South Korea, with each building containing 30–35 floors. The apartment complex was newly constructed and was designed while considering the integration of the proposed system (the system plan was included from the architectural planning stage). The installation locations were the underground spaces of the buildings; a total of nine systems were installed (one for each building). Each building contained 3–6 households per floor; therefore, the total number of vertical drainpipes was 3–6 pipelines per building. The diameters of the vertical and horizontal drainpipes were 100–125 mm. An additional resource recovery device was installed as a backup, and an outside input device was added to allow the residents to manually input the food waste into the system.

2.2. System Operation and Experimental Method

2.2.1. Food Waste Disposer Coupled with Solid Recovery Process: A Pilot-Scale Experiment

The food waste used in our pilot study was primarily based on the actual food waste generated from various Korean restaurants around the research laboratory. The composition analysis of the collected food waste, relative to the standard food waste composition defined by the government for various food waste management certification tests [12], portrayed a higher proportion of grains and lower proportions of fruits and vegetables; therefore, vegetables and fruits were added to the waste to closely resemble the standard food waste composition (Table 1). The final composition of the processed food waste was 25.7–35.9% grains, 40.8–48.5% vegetables, 4.1–12.3% fruits, and 13.5–17.5% fish and meat; except for the proportion of grains, the other proportions closely matched the composition of the standard food waste samples.

Table 1. Food waste composition used in the pilot-scale experiment.

Category	Grain	Vegetable	Fruit	Fish and Meat	Foreign Substance	Total
Experiment (wt%)	25.7–35.9	40.8–48.5	4.1–12.3	13.5–17.5	0.0–1.6	100
Standard food waste composition for the South-Korean context (wt%)	16 ± 2	51 ± 5	14 ± 2	19 ± 2	-	100

Currently, raw food materials are used as standard food waste samples, but this differs significantly from the actual conditions that entail issues such as odor generation and the variations in waste density and size; hence, using leftover food is considered more reasonable [13]. The food waste samples used in this pilot study can be regarded as being closer to the characteristics of the food waste generated in real life, compared to the standard food waste samples. The ultimate goal of our study was to demonstrate the applicability of the proposed system in real apartments, which required replicating the composition of real-life food waste.

For continuous experiments, we considered the amount of food waste input per day for 30 households; based on the statistics of food waste generation per person per day and the average number of family members per household in Korea, the daily food waste generation was calculated to be 14.44 kg/d. In this experiment, the average amount of food waste input was 14.58 kg/d and, according to the results of the preliminary study, the amount of water introduced during the grinding process was set to 15 L/kg of food waste. The total operation period was 25 days, during which the feeding of food waste was conducted for 23 days, and the collection of solid and liquid materials took place during the last 2 days (prior to the completion of the operation). The ground materials were fed into the S/L separation unit three times a day (in the morning, during lunch hour, and at night), in accordance with the times when food waste is generated in real life. The collection of solid materials was performed automatically within 1 h after the feeding.

For the performance assessment and establishment of the mass balance of the system, the amounts of food waste fed into the system, collected solids, and discharged wastewater were measured and the total solid (TS) was analyzed, through which the solid recovery and discharge rates were calculated. In addition, the suspended solid (SS) and dissolved solid (DS) were also analyzed to determine the solid recovery rate based on SS. Furthermore, we analyzed the biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (T-N), and total phosphorus (T-P) of the discharged wastewater. All analysis items were analyzed according to the standard methods [14], and both the system operation and analysis experiments were performed in a laboratory to ensure constant temperature and humidity levels.

2.2.2. Full-Scale System Suitable for an Apartment Complex for the Collective Recovery of Solid Resources from Food Waste

During the study period, the full-scale system, mainly composed of high-rise apartment buildings of at least 30 floors and mostly around 35 floors, was operational since its installation (for about 2.5 years). The premium apartment complex was located in the heart of Seoul, South Korea's capital. In this section, the ratio of dual-income couples was relatively high, and the frequency of dining out was also very high. Therefore, the average daily inflow of food waste grindings introduced into the system was less than planned, with no input at lunch and high inputs in the morning and evening. The disposers (same as those which were considered in the pilot study) were installed under the sink in each household. The operational demonstration of this system prioritized meeting the legal regulatory standard of South Korea (a solid discharge rate of less than 20%). Thus, more emphasis was placed on minimizing the amount of solids discharged into the sewer than maximizing solid recovery.

The primarily recovered solids were ultimately discharged in the form of dried matter, after undergoing the bio-drying process. Aerobic decomposition was promoted by the continuous rotation of the horizontal agitator within the reactor [rotating at 5 ± 1 rotation per minute (rpm)] and ensuring a continuous air supply (0.1–0.2 m^3/min) into the reactor. The average hydraulic retention time (HRT) of the bio-drying apparatus was 14 days, and the final discharge of the dried material from the system was carried out at an average interval of one month, in accordance with the storage capacity of the discharge hopper. The key operating factors, including the internal temperature and moisture content of dried material, were periodically checked throughout the operational period.

The usefulness of the discharged dried material as fuel for renewable energy was analyzed, and its effectiveness as compost and feed was also evaluated. The samples were oven-dried at 105 °C for at least 20 h to determine the moisture and TS contents. The total carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) contents were determined using the sieved samples (after drying) with a FLASH-2000 auto-analyzer (Thermo Fisher Scientific, Bremen, Germany). Furthermore, we determined the high calorific value (HCV) on a dry basis, using a Bomb Calorimeter (PARR 1281, Parr Instrument Co., Moline, IL, USA). The compost quality was analyzed in accordance with the compost analysis methods [15] stipulated by South Korea's Fertilizer Control Act. The heavy metal contents were determined for the extracts obtained after the digestion of the 2 mm sieved samples using concentrated sulfuric acid and 33% hydrogen peroxide at 360 °C. The maturity measurements were conducted using the Solvita® test kit (Solvita and Woods End Laboratories, Mt. Vernon, ME, USA), to assess the stability of the compost based on the concentrations of carbon dioxide and ammonia gas. Moreover, we conducted feed quality analysis in accordance with the methods prescribed in South Korea's Control of Livestock and Fish Feed Act [16]. The contents of aflatoxins, ochratoxin, and melamine were analyzed using high-performance liquid chromatography (HPLC) (Agilent 1100, Agilent Technologies, Santa Clara, CA, USA), and the lead, cadmium, arsenic, and selenium contents were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) (7900 ICP-MS, Agilent Technologies, Santa Clara, CA, USA). The water quality analysis of the wastewater discharged into the sewer was conducted according to the standard methods [14].

The stoichiometric calculation for the theoretical methane potential was performed using Boyle's equation, based on the results obtained from the elemental analysis of the samples [see Equations (1) and (2)] [17].

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_2 + dNH_3 + eH_2S \quad (1)$$

$$B_{th}\left(Nm^3kg^{-1} - VS_{added}\right) = 22.4 \times \left[\frac{(4a + b - 2c - 3d - 2e)\ /8)}{12a + b + 16c + 14d + 32e}\right] \quad (2)$$

The biogas production potential can be estimated from the biochemical methane potential (BMP) test, which is a simple and economical test, where the biogas production is stopped after the insertion of the seed inoculum and substrate into the small anaerobic reactor [18]. A batch-type anaerobic reactor was operated under mesophilic conditions at 38 °C. The anaerobic inoculum used in this study was obtained from a farm-scale anaerobic digester located in Icheon city in South Korea. The inoculum used for the BMP test was incubated under mesophilic conditions for two weeks to eliminate any remaining biodegradable components. The headspace of the serum bottles was purged with N_2 gas and then sealed with a butyl rubber stopper. Furthermore, a blank test was conducted using a batch anaerobic reactor that contained 70 mL of the inoculum; to measure the biogas produced solely by the inoculum, the substrate was omitted. Each anaerobic batch reactor underwent an incubation period that lasted up to 60 days (within a convection incubator). To optimize digestion, manual mixing procedures were performed daily throughout the incubation period. The determination of the ultimate methane potential relied on the volatile solid (VS) content. For precision, the ultimate methane potentials of the samples were adjusted using the blank value and then standardized under standard temperature and pressure (STP) conditions (0 °C and 1 atm, respectively). Gas analysis was performed using gas chromatography (Agilent Model 7890, Agilent Technologies, Wilmington, DE, USA).

3. Results and Discussion

3.1. Applicability Evaluation through Pilot-Scale System Operation

3.1.1. Characteristics of Food Waste According to the Grinding Process of the Disposer

The characteristics of food waste samples before and after grinding were compared. Due to the characteristics of the disposer, the amount of DS dissolved in water increased during grinding compared to before grinding, as the solids were ground together with water. Since the solid recovery device of the system was a physical apparatus, it supported the recovery for SS, and almost no recovery of DS was noted. Therefore, comparing the characteristics of the food waste before and after grinding determined the foundational principle for solid recovery in the system and served as a critical measure for determining the solid recovery rate. The change in solid behavior due to the grinding by the disposer was analyzed; the SS/TS ratio before grinding was 78.8% and after grinding was 59.8%, indicating that 19% of the SS content had dissolved into DS during the grinding process. This indicated that 19% of the SS loss occurred during the grinding process; therefore, theoretically, the maximum weight of particulate solids recoverable after grinding corresponded to 60% of the TS input.

We observed the change in the SS/TS ratio (%) over time after grinding the food waste. Immediately after grinding, the SS/TS ratio was 60%; after analyzing the SS/TS ratio at 1 h intervals, we noted that there was minimal change for up to 1 h. Notably, after 1 h, the SS content began to decrease, and 6 h after grinding, the SS/TS ratio was 49%. This indicated that the SS continued to dissolve into the DS during the post-grinding retention process, and almost no dissolution of SS occurred within 1 h after grinding. Therefore, we conclude that recovering the solids within 1 h after the food waste grindings are input into the system is the most ideal method for maximizing the solid recovery rate. These optimal conditions for the operation of the solid recovery device were applied in subsequent experiments.

3.1.2. Solid Recovery in Pilot-Scale System

The average amount of food waste fed into the system during the operation period was 14.58 kg/d, with an average moisture content of 80.99%, while the average solid fraction of the feed was 2.77 kg/d. The behavior of solids from the fed food waste, collected solids, discharged wastewater, and remnant matter during the operation period is shown in Figure 4. Based on the cumulative amount of solids, 49.60% of the solids fed into the system were recovered as solid matter, while 21.23% were discharged as wastewater and 29.17% remained inside the system.

The solid discharge rate was 21.23%, only slightly exceeding Korea's legal standards, thereby portraying a potential of meeting the requirement. In Europe, ground food waste is either directly discharged into the sewer or transported to sewage treatment plants via collection vehicles [19]. In South Korea, due to concerns about increased loads at sewage treatment plants and sedimentation issues in the sewer systems, strict standards for solid discharge rates are applied when using disposers. In Japan, the wastewater is pre-treated before being drained into the sewage system, using small-scale wastewater treatment units to process the disposed material [20]. This approach considers the negative impact on public sewers, but widespread application is difficult due to the cost and operational and management issues related to wastewater treatment units. Considering the scattered combined sewer systems in South Korea and the challenges associated with installing numerous small-scale wastewater treatment units, the proposed system (which complies with the solid discharge rate standards) can improve the residents' waste management practices, while integrating seamlessly with the existing sewage and waste treatment systems in the country.

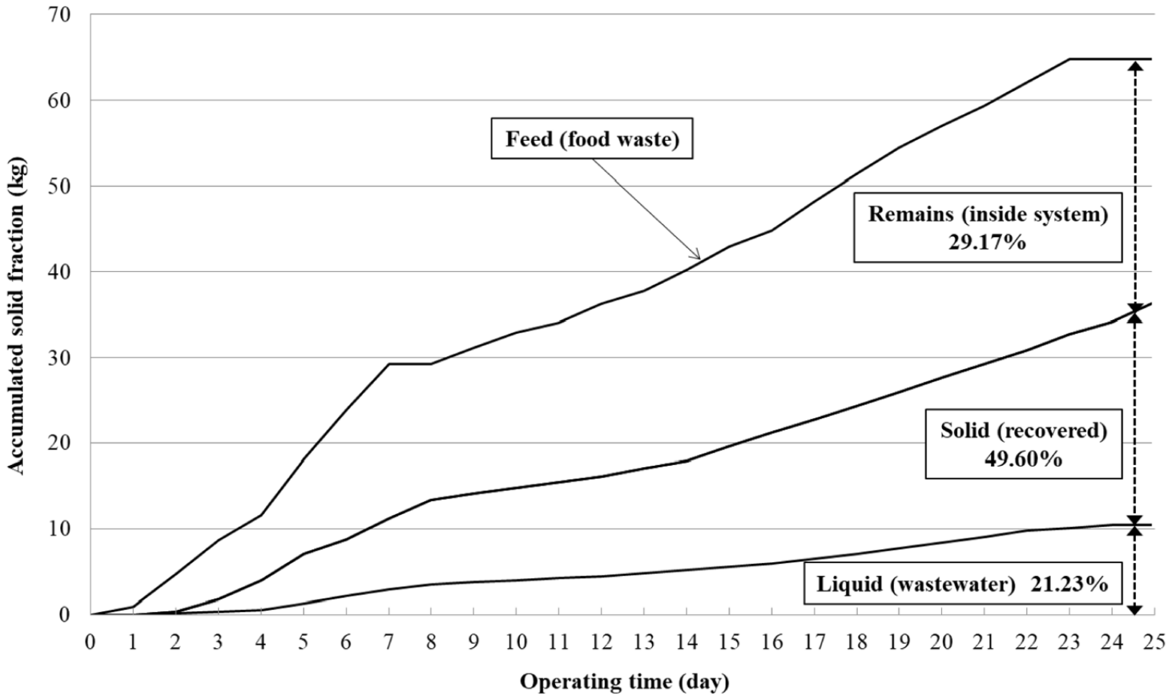

Figure 4. Accumulated total solid (TS) fraction in the feed, collected solid, liquid, and remaining matter.

Using the proposed system, we recovered about 63% of the solids of the waste material, excluding those discharged as wastewater, with the remaining solids accumulated inside the system. As shown in Figure 4, in the first 7 days of the operation, the amount recovered as solids is relatively low, with a large amount of the fed material remaining inside the system. This could be explained by the addition of clean water into the S/L separation unit before operation, which requires a stabilization period of approximately 7 days.

A certain amount of TS remained inside the system. The system had an effective volume of 500 L, and considering the operating conditions, the HRT of the food waste grindings was about 2 days. However, the majority of SS was recovered by the recovery device within 1 h; thus, the solid retention time (SRT) for SS was 1 h. However, after the SS was recovered, some SS and DS forms of the solids that were not recovered remained in the system, with the remaining SS being further recovered or filtered out by the filter device, and the DS being discharged at a constant concentration relative to the continuous inflow. In conclusion, through the pilot-scale experiments, we were able to confirm the possibility of achieving a certain level of solid recovery while also identifying the limitations of solid recovery.

To minimize the solid discharge rate and maximize the solid recovery rate, we improved the system by reducing the space for conversion of SS to DS, by decreasing the effective volume inside the system and shortening the recovery time of the solid recovery device. These improvements were reflected in the manufacturing of the full-scale system for real-life demonstration.

3.1.3. Water Quality of the Discharged Wastewater

Existing food waste disposer systems can be divided into direct discharge models and those that entail pre-treatment before the application of drainage methods [6,19,20]. The first method, mainly used in the USA, involves using the disposer to grind food waste and then discharging all the grindings directly into the sewer (for transport and treatment at the sewage treatment plant). The second method, mainly used in Japan, involves treating the ground food waste through biological treatment or other wastewater treatment processes, before discharging the treated water into the sewer. There have been several pilot projects in South Korea for each method. The quality of the wastewater generated from the method proposed in this study, which entails the separation of solids from the ground food waste and minimizes the solid content in the discharged water, can be expected to outperform the first method and underperform the second method.

The analysis results for the discharged wastewater's BOD, COD_{Mn}, SS, T-N, and T-P content over the operation period of the pilot system are shown in Figure 5. Overall, the concentration of pollutants in the discharged water steadily increased until the mixture stabilized (after about 8 days), portraying similarities to the stabilization trend of solid recovery behavior shown in Figure 4. As the system was filled with water (tap water) at the beginning of operation, the initial water quality data were not meaningful. The concentrations of BOD, COD_{Mn}, SS, T-N, and T-P in the discharged water at the end of the experiment were 4752, 4849, 585, 314, and 86 mg/L, respectively. After 16 days, we noted a significant decrease and increase in the SS and COD_{Mn} contents, respectively. This can be explained by the dissolution of SS in the unrecovered or unreleased solids (to form DS) during the increased retention time inside the system. The decrease in the amount of remaining solids inside the system in the latter part of the experiment, as shown in Figure 4, can be explained by the same reason.

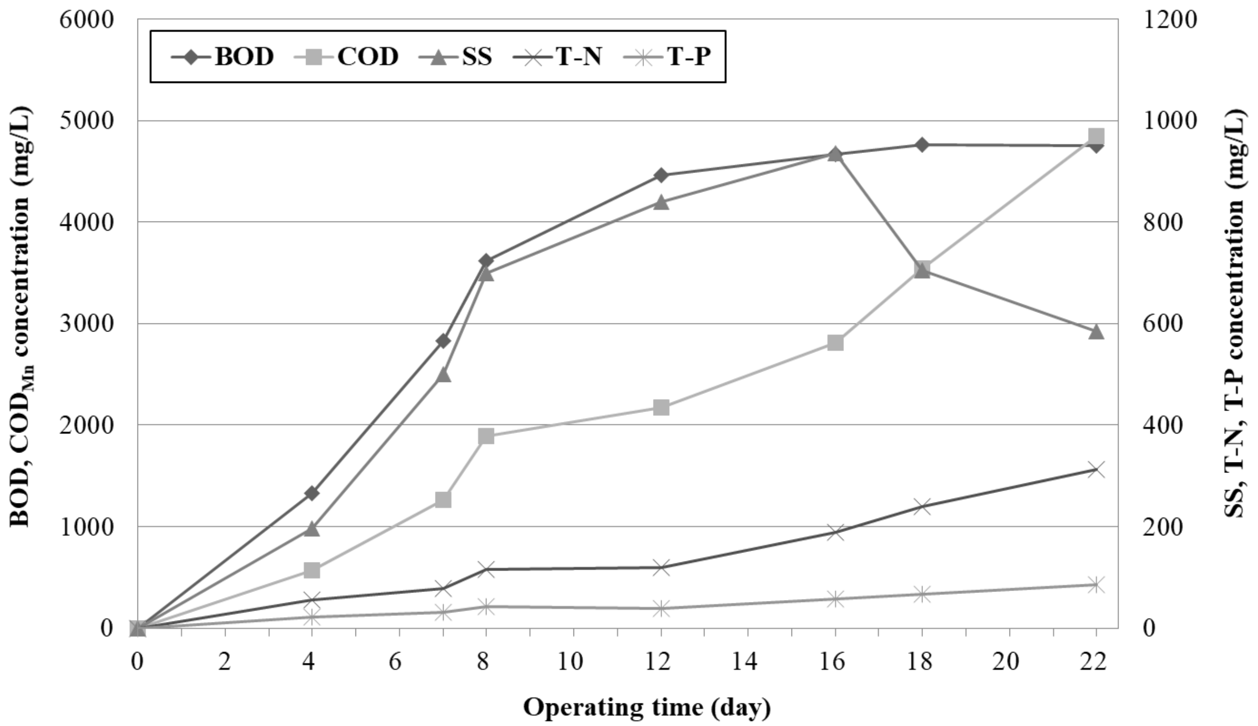

Figure 5. Concentration of water pollutants in the discharged wastewater from pilot-scale system over the experiment operation period.

In this pilot study, a minimum of 15 L/kg of food waste was used for grinding (by the disposer), significantly different from the actual water usage in kitchens. In 2022, the daily water usage per person in South Korea was 305.6 L, with about one-fifth of this amount being used in the kitchen [21]. Considering the actual water usage in residential kitchens, this amounts to approximately 408.6 L/kg of food waste, which is about 27 times more than the previous usage. Assuming the dilution effect of water, the recalculated concentrations for discharged water pollutants, BOD, COD_{Mn}, SS, T-N, and T-P were estimated to be 176.0, 179.6, 21.7, 11.6, and 3.2 mg/L, respectively. These values are lower than the average concentrations in the inflow water of four sewage treatment plants in Seoul, excluding BOD. For reference, as of 2021, the average concentrations of BOD, SS, T-N, T-P, and total organic carbon (TOC) in the inflow water to the four sewage treatment plants in Seoul were 136.6, 107.8, 32.9, 3.5, and 83.3 mg/L, respectively [22].

3.2. Operation of the Proposed Full-Scale System

3.2.1. Applicability of Recovered Solids as Solid Fuel

The solids discharged after undergoing the bio-drying process portrayed a combustible material content of 67.06%, higher heating value (HHV) of 4843 kcal/kg, and lower heating value (LHV) of 3759 kcal/kg, indicating excellent value as biomass–solid refuse fuel (bio-SRF) (Table 2). The contents of carbon, hydrogen, and oxygen, which are major chemical elements that determine the calorific value of the fuel, were 48.85, 6.87, and 40.58%, respectively. Yang et al. [23], in a study conducted in a small village in Japan, reported that the use of disposers increased the content of combustible materials by about 1.7 times and the HHV by about 2.0 times. This is because there is no possibility of foreign material contamination when using a disposer compared to separating and disposing of food waste in bags. In other words, the use of food waste disposers results in high-quality food waste that is free from foreign materials, suggesting that a higher quality recycled product can be obtained for recycling purposes, as long as the solid content can be recovered efficiently.

Table 2. Characteristics of the recovered solid for applicability as solid fuel.

Parameter		Value [1]
Four major components	Moisture (wt%)	14.06 (0.16)
	Combustible material (wt%)	67.06 (1.67)
	Fixed carbon (wt%)	16.15 (0.09)
	Ash (wt%)	2.74 (0.11)
Calorific value	High (kcal/kg, d.b. [2])	4842.68 (13.03)
	Low (kcal/kg)	3758.75 (12.10)
Elemental composition	Carbon (wt%, d.b.)	48.85 (1.44)
	Hydrogen (wt%, d.b.)	6.87 (0.21)
	Oxygen (wt%, d.b.)	40.58 (1.15)
	Nitrogen (wt%, d.b.)	4.03 (0.10)
	Sulfur (wt%, d.b.)	0.25 (0.03)

[1] Mean with standard deviation in parentheses. [2] d.b., dry basis.

3.2.2. Applicability of Recovered Solids as Compost

The value of the solids discharged as compost after the bio-drying process was evaluated; all the analytical items met the Korean compost standards (Table 3). Particularly, the concentration of salt was 0.13 wt% (dry basis), significantly below the domestic legal standard of 2.0 wt%. Several scholars reported the effects of crop stress due to high salt concentration in the soil [24]; caution is advised when fertilizing with compost made from food waste due to its salt content (known to decrease plant growth) [25]. In Korea, the high salt content in the final compost products derived from food waste composting/recycling facilities has been a major issue, resulting in a decrease in the demand for compost products. In contrast, the proposed system significantly reduces this issue, as the salt contained in the food waste would be naturally washed away with water during the grinding process. The maturity (as per the Solvita® method) of the final solid product was four, precisely meeting the domestic legal standard of four or greater. Although the proposed system only included a bio-drying process and no maturation process, we could conclude that the solid material reached a certain degree of maturation, as determined by the Solvita method, due to the material's low moisture content (13.98%). The content of the matter insoluble in HCl was an indicator of the amount of foreign material in the final product, particularly soil content. The content of matter insoluble in HCl was very low (at 0.42 wt%) (the legal standard $\leq$ 25 wt%), which can be explained by the reasons described in Section 3.2.1.

Table 3. Characteristics of the recovered solid for applicability as compost.

Parameter	Value
Organic matter (wt%)	82.75
Total nitrogen (wt%)	3.49
Ratio of organic matter to total nitrogen	23.71
Moisture (wt%)	13.98
Arsenic (mg/kg, d.b. [1])	N.D. [2]
Cadmium (mg/kg, d.b.)	N.D.
Mercury (mg/kg, d.b.)	N.D.
Lead (mg/kg, d.b.)	0.68
Chrome (mg/kg, d.b.)	6.03
Copper (mg/kg, d.b.)	12.29
Nickel (mg/kg, d.b.)	2.66
Zinc (mg/kg, d.b.)	39.81
Escherichia coli O157:H7 (+/− [3])	N.D.
Salmonella spp. (+/−)	N.D.
Salt (wt%, d.b.)	0.13
Maturity (Solvita® method)	4
Matter insoluble in HCl (wt%)	0.42
pH	5.15

[1] d.b., dry basis. [2] N.D., not detectable. [3] +/−, may or may not be detected.

3.2.3. Applicability of Recovered Solids as Feed

The value of the discharged solids as feed (after the bio-drying process) was evaluated, and all the analytical items met the Korean feed standards (Table 4). There were slight differences in some analysis items that overlapped with the compost analysis items. This may be due to the differences in each analysis method and the heterogeneity of the samples obtained from food waste. The nutritional components, such as crude protein, fat, fiber, and ash were 22.79, 3.84, 24.14, and 3.22 wt%, respectively. Heavy metals, such as lead and mercury, were either not detected or detected in trace amounts, which adheres to the standards. Volatile basic nitrogen (VBN) is an indicator that can determine the freshness of food, especially meat or fish, based on the principle of converting amines, such as ammonia and trimethylamine, produced during protein degradation into VBN for measurement [26]. The bio-drying apparatus had an average HRT of 14 days, and the final discharge of the dried material from the system was carried out at an average interval of one month, according to the storage capacity of the discharge hopper; however, the VBN value of 0.05 wt% indicated a fresh state (the legal standard in Korea is less than 0.5). Mold toxins, such as aflatoxins and ochratoxin, were not detected. In Korea's recycling facilities for converting food waste into feed, the waste goes through stages of storage at home and collection containers (which are generally placed at designated spaces on the first floor of apartments), transportation to recycling facilities, and short-period retention in the input storage hopper at recycling facilities, thus entering the recycling process at least three days to a week after being generated at home. In contrast, the proposed system immediately grinds food waste as soon as it is produced in each household and introduced into the solid recovery device, while the waste is still fresh. In addition, organic matter is fermented and dried during the bio-drying process, stabilizing the waste and avoids decomposition and the formation of mold toxins.

Table 4. Characteristics of the recovered solid as for applicability as feed.

Parameter	Value
Moisture (wt%)	13.70
Crude protein (wt%)	22.79
Crude fat (wt%)	3.84
Crude fiber (wt%)	24.14
Crude ash (wt%)	3.22
Salt (wt%, d.b. [1])	0.29
Phosphorus (wt%)	0.20
Volatile basic nitrogen (wt%)	0.05
Lead (ppm)	0.01
Mercury (ppm)	0.01 or less
Cadmium (ppm)	N.D. [2]
Arsenic (ppm)	0.01
Fluorine (ppm)	N.D.
Copper (ppm, d.b.)	10.52
Zinc (ppm, d.b.)	20.58
Selenium (ppm)	0.09
Aflatoxin B_1 (ppb)	N.D.
Aflatoxin B_2 (ppb)	N.D.
Aflatoxin G_1 (ppb)	N.D.
Aflatoxin G_2 (ppb)	N.D.
Ochratoxin A (ppb)	N.D.
Salmonella spp. (+/− [3])	N.D.
Melamine (+/−)	N.D.

[1] d.b., dry basis. [2] N.D., not detectable. [3] +/−, may or may not be detected.

3.2.4. Applicability of Recovered Solids as Substrate for Biogas

The theoretical BMP value of the discharged solids, according to Equations (1) and (2), was 0.477 $Nm^3CH_4/kgVS_{added}$, portraying no significant difference from the typical theoretical BMP values for general food waste [27]. The cumulative methane production curve of the discharged solids based on the BMP test is presented in Figure 6. The final experimental BMP value was 0.399 $Nm^3CH_4/kgVS_{added}$, at the substrate to inoculum (S/I) ratio of 0.32, indicating its suitability for the biogasification treatment. This value is slightly lower than that of typical food waste, which could be attributed to the consumption of biodegradable organics during the bio-drying process. Food waste has a high energy potential that can be converted into useful energy in the form of methane via anaerobic digestion [28]. However, the solids discharged from the proposed system after the bio-drying process, with high organic content and low moisture, would be more suitable for co-digestion with the wet anaerobic digestion process, rather than being used solely for biogasification. Anaerobic co-digestion provides an opportunity to overcome the drawbacks of mono-digestion, by simultaneously digesting two or more feedstocks. Anaerobic co-digestion of food waste, livestock manure, sewage sludge, agricultural byproducts, and industrial byproducts has been extensively studied [29].

3.2.5. Quality Monitoring of Wastewater

The analysis results for the BOD, COD_{Mn}, TOC, SS, T-N, and T-P contents of the discharged wastewater for the full-scale system are shown in Figure 7. The analysis was conducted once a month, over a total of 16 months. Generally, as the operation progressed, the concentration values decreased, and the fluctuation range narrowed. This indirectly indicates that the various performances of the full-scale system stabilized over time. During the experimental period, the BOD, COD_{Mn}, TOC, SS, T-N, and T-P contents ranged from 175 mg/L to 340 mg/L, 93.1 mg/L to 158 mg/L, 117 mg/L to 154 mg/L, 96 mg/L to 222 mg/L, 7.21 mg/L to 14 mg/L, and 1.27 mg/L to 2.25 mg/L, respectively; the average concentrations during the experimental period were 246, 123, 134, 146, 10.1, and 1.79 mg/L, respectively. The values did not deviate much from the concentrations predicted through the pilot study (BOD = 176.0 mg/L, COD_{Mn} = 179.6 mg/L, SS = 21.7 mg/L, T-N = 11.6 mg/L, T-P = 3.23 mg/L), with the only exception being noted for SS. This is because the expansion to full-scale minimized the HRT of the disposer grindings inside the system, which was a conclusion derived from the pilot study. Compared to the average inflow concentrations of the four sewage treatment plants in Seoul, the T-N and T-P contents were very low, while the BOD, TOC, and SS contents were slightly higher. Due to recent issues pertaining to eutrophication in aquatic environments, sewage treatments focus on the removal of N and P [30], and significant costs are incurred for the advanced treatment of N and P. The installation and operation of the proposed system poses a minimal negative impact on the operation of current sewage treatment plants.

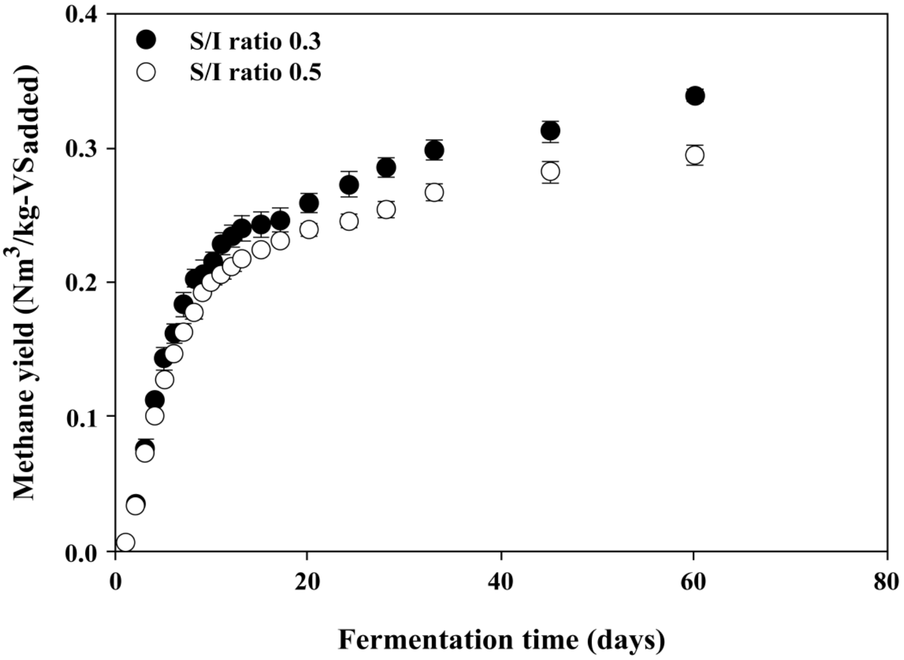

Figure 6. Cumulative methane production curve for the recovered solid with different S/I ratios.

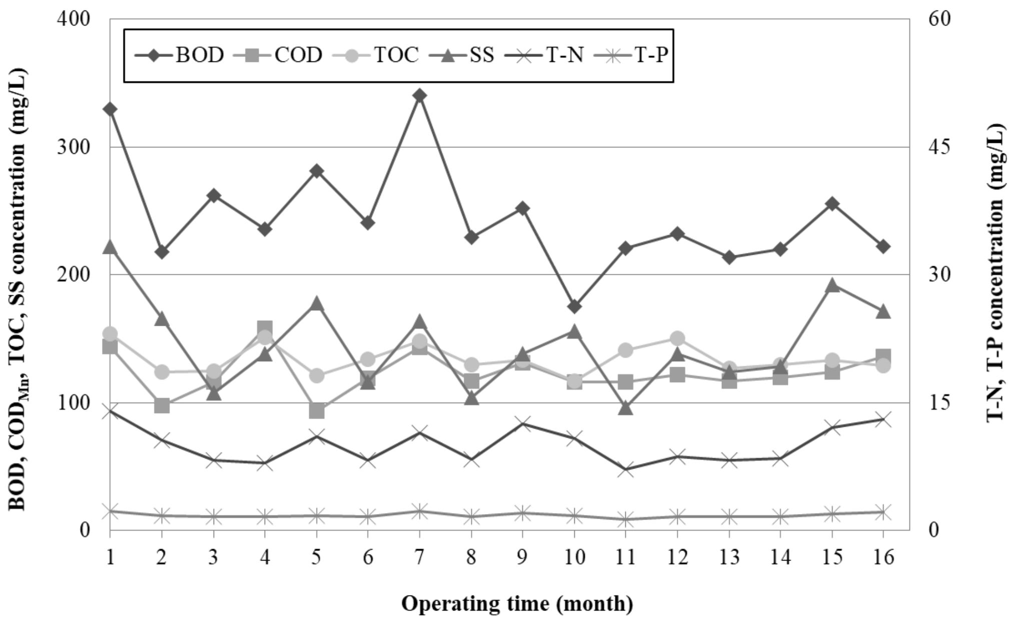

Figure 7. Concentration of water pollutants in the discharged wastewater from full-scale system according to operation time.

4. Conclusions

This study presents a novel food waste disposer model that incorporates a solid recovery process. First, we conducted a pilot experiment to simulate the actual food waste disposer discharge environment to understand the solid recovery performance of the system and the quality of the discharged water. The system's real-world applicability was assessed through long-term continuous operation. In this experiment, 49.60% of the solids fed into the system were recovered as solid matter, while 21.23% were discharged as wastewater, and 29.17% remained inside the system. The BOD, COD_{Mn}, SS, T-N, and T-P concentrations of the wastewater were recalculated while considering the actual water usage in residential kitchens, resulting in values of 176.0, 179.6, 21.7, 11.6, and 3.2 mg/L, respectively. These values are lower than the average concentrations in the water input into the four sewage treatment plants in Seoul, excluding BOD.

Ultimately, a solid resource collective recovery system suitable for the high-rise apartment residence style of South Korea was developed and applied to an actual apartment complex. The solids discharged from the full-scale system, having undergone the bio-drying process, were evaluated for their quality as feed, compost, bio-solid fuel, and biogas substrate. The solids discharged after undergoing the bio-drying process portrayed a combustible-material content of 67.06%, HHV of 4843 kcal/kg, and LHV of 3759 kcal/kg, indicating excellent value as bio-SRF. The results also indicated their suitability as compost and feed, exhibiting significant advantages over the products derived from traditional food waste recycling facility treatments, in terms of the salt and foreign material contents and decay issues. The theoretical BMP of the final discharged solids was 0.477 $Nm^3CH_4/kgVS_{added}$, and the experimental BMP at an S/I ratio of 0.3 was 0.399 $Nm^3CH_4/kgVS_{added}$, suggesting the products' suitability for biogasification treatment. The concentrations of T-N and T-P in the wastewater discharged from this full-scale system, compared to the average concentrations of inflow to the four sewage treatment plants in Seoul, were very low, whereas the concentration of BOD, TOC, and SS were slightly higher. Therefore, we conclude that the installation and operation of the proposed system has a minimal negative impact on the existing sewage treatment plants.

We applied our developed system to a high-rise apartment complex through a pilot study, and the system was operated without major issues. This system is suitable for apartment living environments; however, additional research is needed for application in other residential environments, such as detached housing complexes or community-wide areas. Expanding vertical and horizontal drainpipes and using disposers capable of more roughly grinding food waste will be more advantageous for maximizing solid recovery. Our system is significant in that it can recover valuable resources from food waste without negatively impacting the sewer system, while also enhancing the convenience for residents in separation and disposing of food waste. Additionally, a thorough economic evaluation is essential for the widespread adoption of this system.

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