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Sustainability assessment of retrofitting alternatives for large and old wastewater treatment plants in Seoul

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ABSTRACT

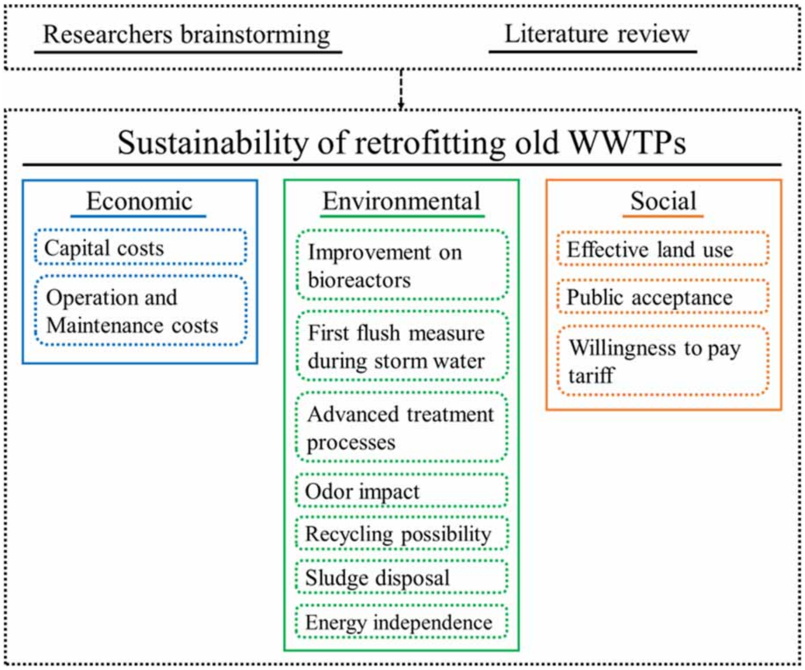
Old wastewater treatment plants (WWTPs) must be upgraded to alleviate the problems associated with aging and reduce their total environmental impacts. To enhance the environmental sustainability in retrofitting large and old WWTPs, the decision-making process for selecting the most appropriate alternative is complicated. In this study, evaluation criteria were proposed to select the most sustainable alternatives for mid- to long-term retrofitting plans for a large WWTP with the treatment capacity of 1.6 M m^3/d, which is initially built in 1987. An analytic hierarchy process was applied to estimate the weights of each criterion. Fourteen experts evaluated the relative importance of criteria through pairwise comparisons. In order to assess the current retrofitting opinions, three retrofitting alternatives were constructed: A focused on energy sufficiency; B expanded the bioreactor capacity and enhancement of the facility for incinerating the sludge leaving the anaerobic digestor; C emphasized the treatment of contaminants of emerging concerns (CECs). A achieved the highest score (0.623) owing to the environmental benefits associated with recycling and first flush stormwater treatment. C exhibited the second highest score (0.612) as the focus on CECs removal. B corresponded to the lowest sustainability (0.426), with the lowest scores pertaining to effective land use and first flush stormwater treatment.

Key words: analytic hierarchical process, effluent quality, energy independence, large WWTPs, retrofitting, sustainability

HIGHLIGHTS

- Proposed retrofitting alternatives for improving energy efficiency and effluent quality.
- Performed AHP to evaluate the weight of the evaluation criteria and alternatives.
- Compared the alternatives via the AHP results, i.e., sustainability scores.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The 2030 Agenda for Sustainable Development proposed by the United Nations consists of 17 Sustainable Development Goals (SDGs). SDG 6 (ensuring the availability and sustainable management of water and sanitation for all) is related to sustainable cities and wastewater treatment plants (WWTPs) (Delanka-Pedige *et al.* 2021). In general, traditional WWTPs do not meet the requirements associated with other SDGs such as climate actions, energy efficiency, or land occupation (Zhang *et al.* 2020) as they are energy- and resource-intensive (Cherchi *et al.* 2015; Heo *et al.* 2021), discharge large amounts of pollutants (Chunyan *et al.* 2015), and emit copious amounts of greenhouse gases (GHGs) (Kyung *et al.* 2015). In addition, many WWTPs are considered unpleasant facilities owing to the health risks associated with odors and noise and inefficient land use in congested cities (Hayes *et al.* 2017). Although wastewater treatment technologies have enhanced access to safe and clean water, WWTPs are negatively evaluated in terms of the SDGs related to energy consumption, participation-oriented urban planning, and discharge of contaminants of emerging concerns (CECs). The sustainability of WWTPs has been typically evaluated in terms of removal efficiency and effluent quality (Lundin *et al.* 1999). However, there exist other important indicators to assess the sustainability of WWTPs, such as the climate change contribution, environmental impacts, and costs that are related to the physical facilities, chemicals, electricity, and materials required for their operation (Wang *et al.* 2018). At present, considering the sustainability requirements for WWTPs, novel evaluation criteria such as sludge disposal, number of labors, or GHG emissions have emerged (Chen *et al.* 2018). To achieve the SDGs of WWTPs, it is necessary to reduce the amount of pollutants in wastewater and encourage environmental sustainability thinking (Seifert *et al.* 2019; Jiang *et al.* 2020; Xi *et al.* 2021). Sustainability thinking is aimed at the minimization of environmental impacts, mitigation of energy and chemical consumption for WWTPs, effective land utilization, GHG mitigation, and generation of increased biogas through effective sludge digestion. These aspects have not yet been considered or prioritized in the design criteria of WWTPs (Callegari *et al.* 2018; Seifert *et al.* 2019; Gherghel *et al.* 2020; Neth *et al.* 2022).

Owing to the growth in population and urbanization, the old WWTPs in large cities typically have insufficient capacity. Moreover, their water and sludge treatment performance is low because of the use of deteriorated equipment and outdated treatment processes, the excessive use of energy and other resources, and first flush from the combined sewer system in rainy seasons. These aspects deteriorate the quality of water received and lead to increased complaints from inhabitants regarding odor and noise. The functionality of aging WWTPs must be upgraded through reinvestment and retrofitting to promote sustainability (Neth *et al.* 2022), for instance, to ensure effluent quality; sludge resourcification; energy independence (considering the concept of water, food, and energy nexus); efficient land usage; resource recovery; reduction of GHG emissions; and removal of CECs such as endocrine-disrupting contaminants (EDCs), pharmaceuticals, personal care products (PPCPs), and antibiotic-resistant bacteria and genes (ARBs and ARGs) (Michael-Kordatou *et al.* 2015; Plakas *et al.* 2016; Zhang *et al.* 2020; Isam *et al.* 2021; Makan *et al.* 2021; Molajou *et al.* 2021; Shao *et al.* 2021; Afshar *et al.* 2022). This reinvestment is especially important, given that the design of traditional WWTPs has been focused on the treatment performance.

Large WWTPs can produce large amounts of energy and achieve energy sufficiency because they incorporate anaerobic digestion processes that generate methane gas from sewage sludge (Zaborowska *et al.* 2021). It is valuable to retrofit old and large WWTPs with respect to efficient resource usage because the input resource efficiency increases with the scale of the treatment facility ($>$100,000 m^3/d) (Jiang *et al.* 2020). To mitigate the risk of nuisance impacting nearby residents and protect the property rights of housing facilities constructed on intrinsic buffer zones surrounding WWTPs, many recommendations have been presented: investment to upgrade the existing infrastructure, insistence on the relocation of WWTPs built earlier than the housing facilities despite no available sites for WWTP relocation within the boundary of the congested city, and the development of multiple cultural complexes including cinemas, department stores, and restaurants above ground and WWTPs underground. However, the renovation of underground WWTPs to increase the volume of treated wastewater may be extremely challenging as the population continues to increase.

The abovementioned investments to enhance the sustainability are also beneficial in terms of global (carbon footprint) aspects such as nutrient recovery, energy production, and economic value (Callegari *et al.* 2018). However, the decision-making process for selecting the most appropriate alternative is complicated because the optimal solution depends on the various criteria and their weights (Plakas *et al.* 2016). The selection of alternatives can be facilitated by evaluating the corresponding sustainability using a set of several indicators (Kamami *et al.* 2011). Various methods have been developed for sustainability assessments, with multi-criteria analysis being a representative technique. Several researchers have applied the multi-criteria decision analysis method as it can help decision-makers select the most sustainable option among a variety of alternatives that may often have conflicting performances. Muga & Mihelcic (2008) presented environmental, social, and economic indicators to evaluate the sustainability of wastewater treatment processes. Molinos-Senante *et al.* (2014) evaluated the sustainability of small-scale WWTPs by calculating the relative importance values of environmental, social, and economic criteria using an analytic hierarchy process (AHP) method and developing integrated indicators. Plakas *et al.* (2016) evaluated the sustainability of tertiary treatment technologies to eliminate micro-pollutants in the effluent through a method termed a simple multi-attribute rating technique exploiting ranks. Zheng *et al.* (2016) developed a decision-making model for wastewater infrastructure alternatives that reflects stakeholder preferences using the multi-attribute utility theory. Vidal *et al.* (2019) presented 12 criteria related to the environment, economy, society, technology, and health to evaluate the sustainability of small-scale onsite sanitation systems incorporated mainly in suburban areas and used ELECTRE III to calculate the importance of indicators. In general, the importance of sustainability metrics can be calculated and evaluated through the AHP and gray relational analysis (Zeng *et al.* 2007) or techniques such as the weighted sum model (Isam *et al.* 2021), fuzzy-based AHP and PROMETHEE-II (D'Silva *et al.* 2021), cardinal weighting, and PROMETHEE (Makan *et al.* 2021).

Notably, the evaluation indicators must be selected considering the object and purpose of the evaluation (Cossio *et al.* 2020). To evaluate the sustainability of retrofitting alternatives of WWTPs, proper criteria must be identified and any necessary tradeoff among the criteria must be considered while selecting the optimal alternative (Ali *et al.* 2020). For example, the balance between 'effluent standards' and 'related impacts' must be ensured because the rigorous effluent standards may lead to increased cost, energy consumption, and GHG emissions of a WWTP (Zhang *et al.* 2020). Weighting methods based on brainstorming, literature review, or personal priorities and interests have been developed (Iacovidou & Voulvoulis 2018; Lizot *et al.* 2021). The AHP method is typically used for quantitatively weighting the contradictory criteria in many sewerage industries (Lee *et al.* 2021; Zhang *et al.* 2022).

However, the selection of the retrofitting alternatives is highly complex in this framework. WWTPs must be upgraded considering the feasibility of upgraded technologies, effective integration with existing facilities, or economic aspects (Rashid *et al.* 2020). Retrofitting must be based on the tradeoff between the improvement of effluent quality and the negative effects of the reinvestment (Bertanza *et al.* 2018). In addition to technical development and adherence to regulations, social acceptance must be ensured (Huh *et al.* 2020). Consequently, it is essential to develop a decision model considering new requirements, especially those related to sustainability, to extend the lifetime of large, aging WWTPs.

To this end, this study was aimed at developing a decision-making model for large-scale and old WWTPs and identifying the most suitable retrofitting alternatives on the Seo-Nam operated by Seoul City. The retrofitting alternatives were proposed to be applicable in the mid- to long-term projects on the WWTP, which mentioned about energy-saving and improvement on the effluent quality. The evaluation criteria were selected by researchers through brainstorming sessions and several workshops. To reflect the recent environmental issues, new regulations, and current state and future direction of the WWTP, the weights of the criteria and experts' preferences were determined by administering a questionnaire to certain sewerage experts. In order to compute the weights of the criteria through opinions of the experts, the AHP method was used. The AHP determined both the weights of evaluation criteria and the preference of the alternatives. The sustainability of the alternatives was assessed through results of the weights of the evaluation criteria and the alternative preference.

2. METHODS

2.1. Study area

WWTP Seo-Nam, constructed in 1987, has four separate wastewater treatment systems and three separate sludge treatment systems (1,630,000 m^3/d, equivalent to the capacity for a population of approximately 3.8 million). Originally, the wastewater treatment systems consisted of two separate conventional activated sludge treatment (AST) systems. In 2014, a new treatment system for nutrient removal was introduced, and the existing systems were transformed into one AST system (capacity: 120,000 m^3/d) and two modified Ludzack–Ettinger (MLE) systems (capacities: 403,000 and 747,000 m^3/d). Furthermore, a new four-stage biological nutrient removal (BNR) system (capacity: 360,000 m^3/d) was introduced in 2019. Although the AST system is in operation at present, there are plans to change it to a four-stage BNR system and increase its capacity to 320,000 m^3/d after several years (Seoul 2021). Recently, several fishers filed complaints, stating that the declining fish catch may be attributable to the appearance of ribbon worms owing to the deteriorated quality of the effluent and receiving water. In the corresponding investigation, 3.9 ± 0.9 mg/L of galaxolide (HHCB), 2.9 ± 2.7 mg/L of tonalide (AHTN), and 0.7 ± 0.4 mg/L of musk ketone (MK) were detected, highlighting the risks of micro-pollutants (Seoul 2019). In addition, in an investigation on the micro-plastic content in the influent and effluent and receiving water, 52 and 0.2 particles of micro-plastic per liter were detected in the influent and effluent, respectively, with the removal efficiency at the WWTP Seo-Nam being 99%. Nevertheless, the micro-plastic content in the effluent must be continually monitored. Additionally, in the rainy season, the biological oxygen demand in the receiving water (River Han) is 68%, resulting from combined sewer pipes and the discharge of untreated wastewater from WWTPs (Seoul 2017a). To address this problem, first flush stormwater treatment facilities with a capacity of 720,000 m^3/d were introduced in the WWTP Seo-Nam in 2021 (Seoul 2019). There are plans to increase the corresponding capacity to 3,100,000 m^3/d (Seoul 2019).

Since 1987, the plant had been operating with two sludge treatment systems, but a new system was added in 2019. At present, the three treatment plants are being separately operated. The raw and surplus sludge from the coagulation/sedimentation and biological processes are concentrated through a gravity belt thickener, centrifugal concentrator, and dissolved air flotation device; digested in an anaerobic digester; and dewatered using a filter press, a centrifugal dehydrator, and a belt press. The dewatered sludge is disposed of through landfilling, consignment, and drying or incineration. Notably, sustainable solutions to dispose of and enrich the value of the waste sludge must be urgently identified. In particular, conventional methods are not environmentally-friendly; it is challenging to secure land for landfilling; there is a significant dependence on external facilities or other cities to dispose of the sludge; and by-products such as fine dusts, odor, and ashes are typically generated. Although drying facilities produce pellet fuel from the waste sludge that can be used in coal-fired power plants, the use of pellet fuel is not desirable owing to the generation and release of fine and ultra-fine particulate matter in the air. As the expiration date of the landfill site use contract with Incheon, which is the neighboring city, approaches, Seoul must identify appropriate landfilling or incineration sites to dispose of household waste including sewage sludge. However, the establishment of waste incineration facilities is not a promising strategy because of the prominent 'not-in-my-backyard' (NIMBY) sentiment that has emerged with increasing complaints against WWTPs.

The population in the treatment area of WWTP Seo-Nam recently increased with the construction of a new town, Magok, resulting in an increase in the amount of influent. At present, the daily average influent exceeds 90% of the capacity, which makes it difficult to comply with the effluent criteria. The WWTP has been noted to exceed the effluent standards of total nitrogen several times in recent years, especially in winter. The effluent standards are expected to become more stringent by 2040, and thus, retrofitting plans must be made to improve the effluent quality.

2.2. Selection of criteria to evaluate the sustainability

To evaluate the sustainability of the mid- to long-term retrofitting plans of WWTPs, the triple bottom-line approach to sustainability was followed (Molinos-Senante *et al.* 2014). The evaluation criteria were presented as hierarchical structural diagrams in three dimensions: economic, environmental, and social. The assessment criteria for retrofitting old WWTPs are shown in Figure 1. Figure 1 presents a framework which is based on results of experts' brainstorming, then 12 subcriteria were selected to assess the sustainability of retrofitting old WWTPs.

The economic dimension involved two criteria: capital costs and operation and maintenance (O&M) costs. In general, the capital cost determines whether an alternative is reasonable depending on the budget allocation. The O&M costs indicate the financial sustainability of processes. The increase in the O&M costs due to the upgrading alternatives must be evaluated.

The environmental dimension consisted of seven criteria: improvement of bioreactors, introduction of first flush treatment during storm events, advanced treatment processes, odor impact, recycling possibility, sludge disposal, and energy independence. The improvement of bioreactors is related to the sustainability of WWTPs. With the development of new biotechnical processes, many old WWTPs are requiring retrofitting or upgrading to satisfy the future stringent effluent standards and enhance the treatment performance. Moreover, the receiving water bodies are polluted by combined sewer overflows. Therefore, the first flush of rainwater that includes a high concentration of pollutants must be treated, especially in old cities that adopt a combined sewer system. Advanced treatment processes can help treat micro-pollutants. Old WWTPs must be retrofitted to improve the effluent quality, especially to manage CECs such as microplastics, EDCS, PPCPs, ARBs, and ARGs. Odor impact can be considered a social dimension (Muga & Mihelcic 2008; Molinos-Senante *et al.* 2014). However, because odor negatively affects not only the public but also the ecosystem, it was considered to be an environmental dimension in this study. Sludge disposal must be considered in the evaluation of sustainable WWTPs. Typically, sludge landfilling is associated with low sustainability owing to the difficulty in securing landfill areas and concerns regarding soil contamination. Attempts should be made to secure an incineration site that avoids NIMBY confrontation with inhabitants. In addition, drying sludge to generate fuel for coal-fired power plants is not a sustainable solution as it may lead to air pollution. Energy independence is one of the key requirements to meet the SDGs. The aging WWTPs that are energy-intensive must achieve energy independence, and it is

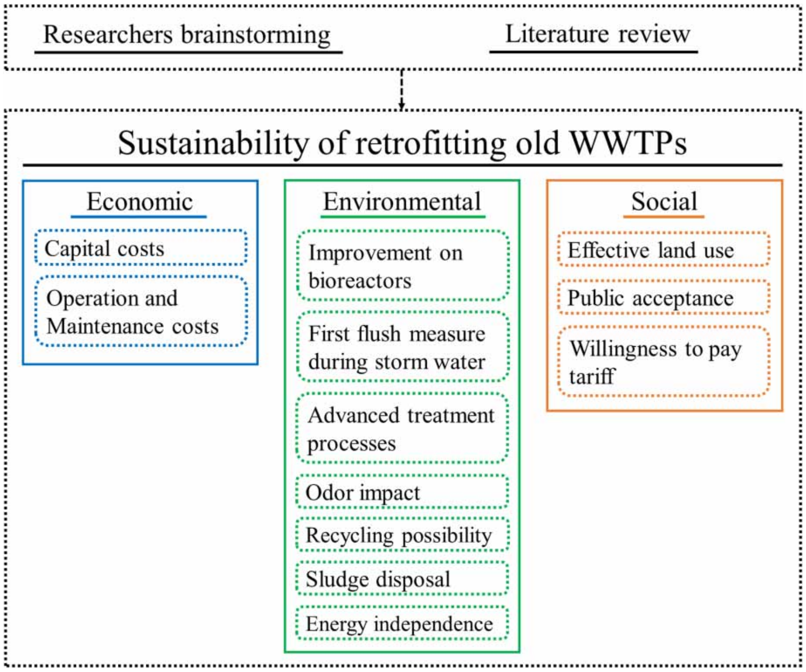


Figure 1 | Proposed evaluation criteria for assessing the sustainability of retrofitting old WWTPs.

desirable to establish net-zero energy WWTPs that produce energy during wastewater and sludge treatment (Myszograj *et al.* 2021).

The social dimension involved three criteria: effective land use, public acceptance, and willingness to pay the tariff. Old WWTPs, which were constructed in suburban areas, are now located in the city center because of urbanization and city expansion and are subjected to increasing pressure to efficiently use the installation site and surrounding land (if available) or be relocated (despite the scarcity of land within the city boundary). In terms of public acceptance, it is necessary to ensure agreement among stakeholders including nearby residents and bystanders before establishing and implementing the plan to upgrade WWTPs. It is important to reflect the public's opinion in the retrofitting plans and lessen the antipathy to WWTPs. In addition, the tariff is affected by the investment scale and O&M costs depending on the retrofitting alternatives. The retrofitting plans must take into account the backlash of citizens and disagreement in the city council in implementing the WWTP-upgrading projects because of a rapid rate increase.

2.3. Weighting system based on the AHP

The AHP is a hierarchical decision-making method based on evaluation factors. The evaluation criteria are hierarchized, and their relative importance is determined through pairwise comparison (Saaty 1980). This method can simultaneously consider and evaluate qualitative and quantitative factors and help make optimal decisions using expert subjectivity and existing data (Bottero *et al.* 2011).

By applying the comparison intensity scale presented in Table 1, i.e., the nine-scale chart proposed by Saaty (1999), experts can evaluate the relative importance of two criteria through pairwise comparison. For instance, if A is more (less) important than B, then A (B) is assigned nine points.

The pairwise comparison matrix is an inverse matrix in which $a_{ij} = 1/a_{ji}$ and the diagonal values are all 1. $A = [a_{ij}]$ represents the relative importance of criterion i with respect to criterion j. The importance of the evaluation item is calculated through the eigenvector and the eigenvalue of the pair comparison matrix.

Next, the consistency of the answers obtained through the survey is reviewed. The consistency index of the response elements is evaluated using the following equation:

$$\mathrm{CI} = \frac{(\lambda_{\max} - N)}{N - 1} \tag{1}$$

where $\lambda_{\max}$ is the maximum eigenvalue calculated by averaging all eigenvalues, and N is the number of elements, the priority of which is to be judged. The maximum value of the eigenvalue is always greater than or equal to N, and a value closer to N corresponds to a more consistent response obtained by the pairwise comparison matrix A (Saaty 1980).

The consistency ratio is obtained by dividing the consistency index by the random consistency index (RI).

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

A CR of 0 means that the pairwise comparison was performed, while the respondent maintained full consistency. The consistency ratio must preferably be less than 10% (Vargas & Dougherty 1982).

Table 1 | Saaty's comparison intensity scale (Saaty 1999)

Intensity	Definition	Description
1	Equally important	Two objectives are equally important
3	Slightly more important	One objective is slightly more important than the other
5	Strongly more important	One objective is strongly preferred over the other
7	Extremely more important	One objective is extremely more favorable
9	Absolutely more important	One objective is absolutely predominant in comparison
2, 4, 6, 8	Intermediate values	Intermediary level between two values

In this study, the following steps were performed to weigh the importance of the sustainability evaluation criteria using the AHP technique:

Step 1: An evaluation criterion was proposed by creating a hierarchical structure. The highest-level goal was to evaluate the sustainability of mid- to long-term retrofitting plans. The structure was divided into environmental, economic, and social criteria and includes each substandard.

Step 2: A pairwise comparison of the evaluation indicators was performed by experts using Saaty's 1–9 relative measurement scale. The relative importance of the evaluation criteria was calculated by constructing a pairwise comparison matrix. Table 2 presents an example of pairwise comparison, in which a certain expert considered the environmental criteria to be three times more important than the economic criteria.

Step 3: The scores of alternatives for evaluation criteria were calculated by conducting a preference survey for each alternative. For example, a questionnaire that included the preferences of alternative evaluation criteria was administered, in which the experts assigned quantitative scores for each alternative.

Step 4: The relative importance of the evaluation criteria was calculated by obtaining the eigenvector of the pairwise comparison matrix of the evaluation criteria, and the scores of the alternatives were calculated using this eigenvector and the normalized relative importance.

Step 5: To examine the reliability of the answer, the CR was calculated and ensured to be lower than 10%.

2.4. Questionnaire

A questionnaire was administered to sewerage experts to obtain their opinions regarding the importance of certain factors. The answers of 14 wastewater treatment experts were obtained. The survey group consisted of six professors, three researchers from government-funded institutions, and five WWTP operation engineers. The experts' answers were designated as Q_n, and a pairwise comparison matrix was constructed using the geometric mean values of all answers.

3. RESULTS AND DISCUSSIONS

3.1. Treatment alternatives

Three retrofitting alternatives for WWTP Seo-Nam were proposed to address the existing sustainability challenges, for example, energy efficiency, stringent future effluent quality, and management of micro-pollutants in the effluent (Seoul City 2018a, 2021). Certain plans also considered odor mitigation in sewer networks, methods to upgrade WWTPs, and citizen communication strategies suggested by officials, sewerage experts, and representative citizens in the sewerage policy forums (Seoul 2017b, 2018b). Tables 3 and 4 present the physical characteristics of the wastewater and sludge treatment systems of the WWTP, respectively. Figure 2 shows a schematic layout of treatment alternatives and the present treatment. Each alternative aims to improve on shortcomings of the current treatment scheme.

Alternative A aims to increase energy efficiency and production through stepwise renewal and replacement of wastewater and sludge treatment systems. The average annual energy consumption in WWTP Seo-Nam in the last 5 years was 156,156 MWh, 73% of which corresponded to blowers and pumps. The old pumps and blowers can be replaced by more efficient devices to save energy. Specifically, energy savings of 7 W/m^3 can be realized by replacing the aging blowers and pumps used in the MLE process: 10 out of 21 blowers and 6 out of 12 blowers must be replaced because their energy efficiency is low (Seoul 2021). In addition, according to a biochemical methane potential test (Seoul 2021), the potential of the biogas in the WWTP can be increased by up to 160% to enhance the efficiency of biogas production. Retrofitting the sludge treatment

Table 2 | Example of pairwise comparison of dimensional criteria

	Intensity of importance																	
Criteria	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Criteria**
Economic											✓							Environmental
Economic								✓										Social
Environmental														✓				Social

Table 3 | Wastewater treatment scheme alternatives

	Plant no.	Primary sedimentation	Biological reactor	Secondary sedimentation	Advanced treatment process	First flush treatment facilities[a]
Present	#1-1	Rectangular clarifier: 120,000 m^3/d	AST: 120,000 m^3/d	Non-metal chain flight	Absence	–
	#1-2	Rectangular clarifier: 419,000 m^3/d	MLE: 403,000 m^3/d	Moving siphon		
	#2	Rectangular clarifier: 769,000 m^3/d	MLE: 747,000 m^3/d	Moving siphon		
	#3	Upflow clarifying filter: 360,000 m^3/d	Four-stage BNR: 360,000 m^3/d	Chain link flight		720,000 m^3/d
A[b]	#1-1	Upflow clarifying filter: 320,000 m^3/d	Four-stage BNR: 320,000 m^3/ d	Non-metal chain flight	Absence	640,000 m^3/d
	#1-2	Upflow clarifying filter: 320,000 m^3/d	Four-stage BNR: 320,000 m^3/d			640,000 m^3/d
	#2	Upflow clarifying filter: 630,000 m^3/d	Four-stage BNR: 630,000 m^3/d			1,260,000 m^3/d
	#3	Upflow clarifying filter: 360,000 m^3/d	Four-stage BNR: 360,000 m^3/d			720,000 m^3/d
B[c]	#1-1	Upflow clarifying filter: 285,000 m^3/d	Four-stage BNR: 355,000 m^3/d	Gould Type II	Absence	640,000 m^3/d
	#1-2	Rectangular clarifier: 273,000 m^3/d	MLE: 466,000 m^3/d	Gould Type II		–
	#2	Rectangular clarifier: 568,000 m^3/d	MLE: 948,000 m^3/d	Gould Type I		
	#3	Upflow clarifying filter: 352,000 m^3/d	Four-stage BNR: 368,000 m^3/d	Gould Type I		720,000 m^3/d
C[d]	#1-1	Upflow clarifying filter: 320,000 m^3/d	Four-stage BNR: 320,000 m^3/ d	Non-metal chain flight	Fine filtration and ozone/ activated carbon	640,000 m^3/d
	#1-2	Upflow clarifying filter: 320,000 m^3/d	Four-stage BNR: 320,000 m^3/ d			640,000 m^3/d
	#2	Rectangular clarifier: 769,000 m^3/d	MLE: 747,000 m^3/d			–
	#3	Upflow clarifying filter: 360,000 m^3/d	Four-stage BNR: 360,000 m^3/d			720,000 m^3/d

[a] The first flush was treated with the upflow clarifying filter using chemicals.

[b] The previous treatment systems were replaced with the efficient technologies and equipment for reducing the energy consumption (Seoul 2021).

[c] Considering the results of EQPS (simulation of the treatment performance according to the daily maximum inflow that meets the effluent standards in 2040), the capacity of the bioreactors must be increased. To increase the concentration of MLSS in the bioreactors, Gould-type sludge collectors in the secondary sedimentation systems were replaced, and a bypass line from the primary clarifier was constructed. The capacity (2,800–3,500 mg/L) of the MLSS could be increased to 4,000 mg/L (Seoul 2021).

[d] To increase the removal efficiency of nitrogen, a four-stage BNR process was introduced in plant #3 (Seoul 2021). In addition, by introducing an advanced treatment process at the end of the secondary sedimentation, micro-pollutants such as CECs, PPCPs, EDCs, ARBs, and ARGs could be managed. Particle pollutants such as microplastics could be treated by fine filtration, and the other micro-pollutants could be treated by the ozone and activated carbon processes (Seoul 2021).

system to an anaerobic two-phase digestion method, introducing a mechanical stirrer, and adding solubilization equipment can enhance the digestion efficiency of the digester and increase the biogas yield by 26, 10, and 8%, respectively (Seoul 2021). Additional energy can be produced using expanded drying facilities that can generate more pellet fuel from the dewatered sludge that can then be disposed without landfilling or consignment (Seoul 2021).

Alternative B aims to improve the WWTP performance by enhancing the bioreactor capacity. Due to the increase in the inflowing wastewater, which reduces the removal efficiency, the daily average inflow is 90% of the capacity and excessive wastewater inflows during wet weather or specific periods. This might be one of the reasons why the treated effluent violates the nitrogen discharge standard in certain scenarios and why the capacity of bioreactors must be increased. The Effluent Quality Prediction System (EQPS), which is a Korean language version of the Super Model (SUMO 21.0.0, manufactured by Dynamita, France), was used for wastewater treatment process modeling. Using the EQPS software, the expanded capacity of the bioreactors was simulated considering the daily maximum inflow in 2040 and anticipated stringent regulation for 2040, i.e., an effluent discharge limit of (T-N 10–15 mg/L). According to the simulation results, the capacity must be increased to

Table 4 | Sludge treatment scheme alternatives

	Plant no.[a]	Thickening	Digestion	Mechanical dewatering	Final disposal method (capacity of facilities)[b]
Present	#1	Gravity belt and centrifugal	Two-phase anaerobic digestion	Filter press	Sludge drying facility: 285 t/d Sludge incinerator: 150 t/d
	#2		Two-step anaerobic digestion	Centrifugal	
	#3	Air flotation	One-step anaerobic digestion	Filter press	
A[c]	#1 #2 #3	Gravity belt and centrifugal	Two-phase anaerobic digestion[d]	Filter press	Sludge drying facility: 555 t/d Sludge incinerator: 150 t/d
B[e]	#1	Gravity belt and centrifugal	Two-phase anaerobic digestion	Filter press	Sludge drying facility: 285 t/d Sludge incinerator facility: 420 t/d
	#2		Two-step anaerobic digestion	Centrifugal	
	#3	Air flotation	One-step anaerobic digestion		
C[f]	#1 #2	Gravity belt and centrifugal	Two-phase anaerobic digestion	Filter press	Sludge drying facility: 285 t/d Sludge incinerator facility: 420 t/d
	#3	Air flotation	One-step anaerobic digestion	Centrifugal	

[a] The sludge treatment systems consists of three plants. Plant #1 of the sludge systems treats the sludge from plants #1-1 and #1-2 in the wastewater system.

[b] Thirty-five percent of sludge in the WWTP Seo-Nam is disposed of at a drying facility and coal-fired power plants, 22% is incinerated, and 43% is landfilled and treated via consignment. To independently and sustainably dispose of the waste sludge, the municipality planned to expand the drying facilities. Notably, the use of sludge pellets fuel must be prohibited in coal-fired power plants because its ash produces fine and ultra-fine particulate matter leading to air pollution.

[c] The old motors in the thickening and dewatering processes were changed, reducing electricity consumption by 46% (Seoul 2021).

[d] To increase the biogas and energy yields, two-phase anaerobic digestion systems were introduced. A mechanical stirrer was used to replace the existing gaseous stirrer to improve biogas production by 10% (Seoul 2021). Sludge solubilization with an ultrasonic equipment was introduced to increase the sludge treatment and biogas production by 8% (Seoul 2021).

[e] The previous sludge treatment scheme was retained in this alternative, except the sludge incinerator was expanded to limit the operation of drying facilities producing sludge pellet fuel.

[f] The two-step anaerobic digestion system was undesirable because of its low biogas yield. To address this problem, the two-phase anaerobic digestion system was introduced in plant #2 (Seoul 2021). To address the issues related with the sludge drying facilities and pellet fuel, the capacity of the sludge incinerator was expanded.

507,000 m^3/d, and several parts of the existing primary clarifier must be replaced by bioreactors to reduce the construction cost by not constructing a new treatment system, given the limited available land (Seoul 2021). Moreover, the existing sludge collectors and siphon and chain flight systems cannot maintain a high concentration of mixed liquor suspended solid (MLSS), especially in winter. Consequently, this alternative aims to increase the efficiency of denitrification by maintaining higher MLSS concentration in the bioreactors. To this end, a bypass line from the primary clarifier would be constructed, and the sludge collection method of the secondary clarifier would be improved to increase the surplus sludge collection rate through replacement with Gould-type collectors (Seoul 2021). The introduction of new collectors can help increase the MLSS concentration (2,800 mg/L at present) to 4,000 mg/L. Finally, an incinerator can be used to dispose of a large amount of sludge. The incinerated ashes can be recycled as a fertilizer or disposed via landfilling. Given the challenge in constructing a new incinerator owing to the residents' disapproval, this plan is based on the premise that an agreement can be reached by collecting and reflecting opinions from public officials, stakeholders, and residents.

Alternative C aims to improve the effluent quality with advanced treatment technology. This retrofitting plan includes the replacement of the new bioreactors to increase the denitrification efficiency. The bioreactor in plant #1-1 (Table 3) will involve a four-stage BNR process to effectively eliminate the nitrogen in the wastewater, and a highly advanced treatment process (tertiary treatment) will be introduced to remove microplastics and synthetic musk that represents current environmental and social issues. The advanced treatment processes include microfiltration, advanced oxidation technology (ozone), and activated carbon adsorption. Particle pollutants such as microplastics can be treated via microfiltration, and PPCPs such as synthetic musk can be treated via ozone and activated carbon adsorption (Seoul 2021). Additionally, this alternative can increase the possibility of recycling higher-quality treated water. Finally, this alternative involves the installation of incinerators, with the same considerations as those in alternative B.

3.2. Evaluation criteria

Table 5 presents the indicators of the evaluation criteria and their quantitative and qualitative descriptions. These indicators were provided to the experts to weigh the evaluation criteria and alternatives.

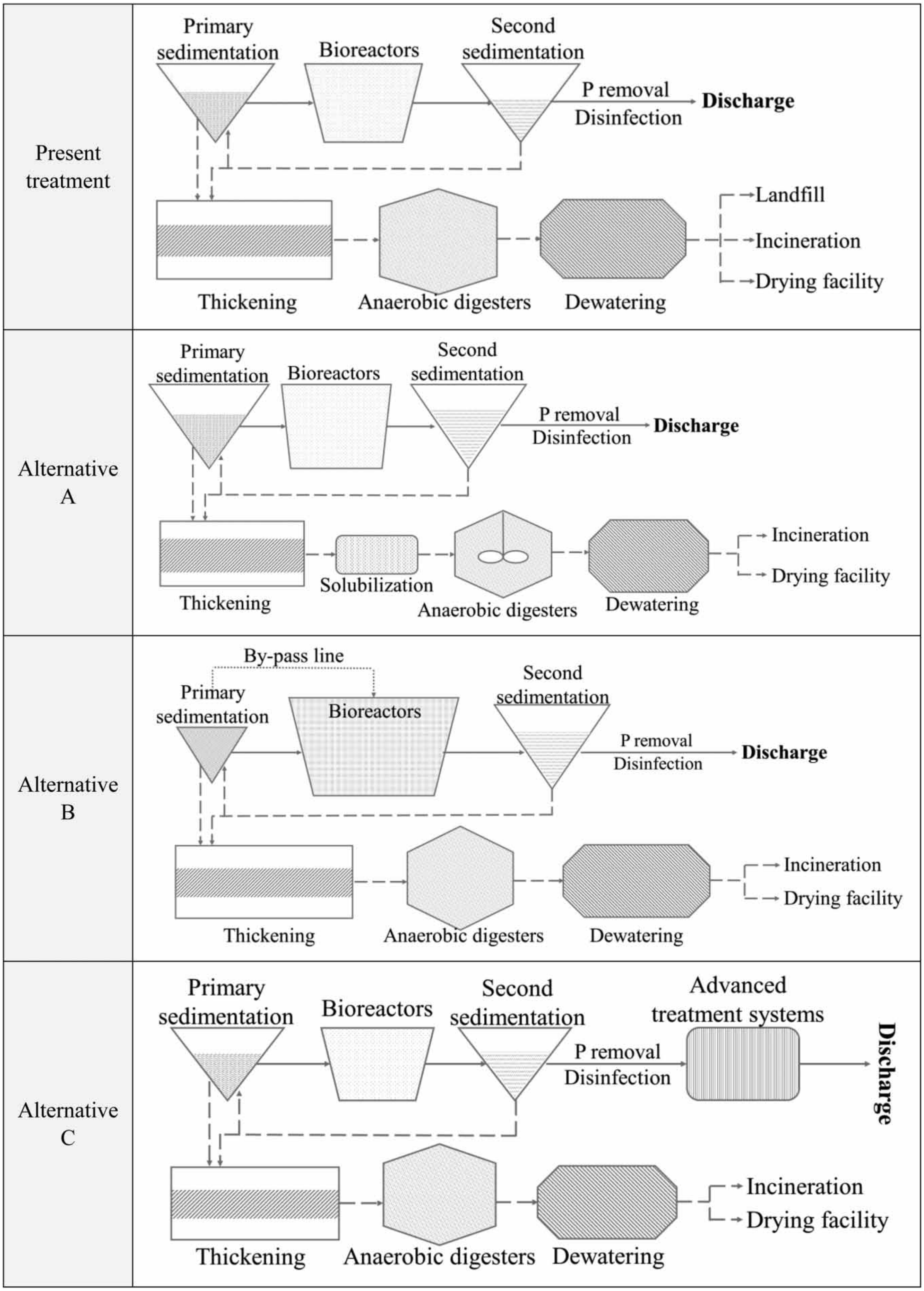


Figure 2 | Treatment schemes of the retrofitting alternatives and present scheme. Solid line = wastewater line; dotted line = sludge line.

Table 5 | Evaluation matrix of the upgrading alternatives of the old WWTP

		Indicators		
Dimensions	**Evaluation criteria**	**A**	**B**	**C**
Economic	Capital cost (KRW)	2,290,056 million	1,084,791 million	2,700,810 million
	O&M cost (Increase rate)	Low	Medium	High
Environmental	Improvement of bioreactors	Four-stage BNR	MLE + four-stage BNR	MLE + four-stage BNR
	First flush treatment during the storm event (m^3/d)	3,260,000	1,360,000	2,000,000
	Advanced treatment processes	Absence	Absence	Fine filtration and ozone/ activated carbon
	Odor impact (Increase rate)	Low	Medium	Low
	Recycling possibility	Sludge pellet (339 t/d) Gray water	Sludge pellet(220 t/d) Gray water	Higher quality of treated water
	Sludge disposal	Drying 100%	Drying 42% + incineration 58%	Incineration 100%
	Energy independence (%)	84	76	79
Social	Effective land use	Medium	Low	Medium
	Public acceptance	Low	Medium	High
	Willingness to pay tariff	High	Medium	Low

Note: High, medium, and low pertain to relative comparison among the alternatives.

3.2.1. Capital costs

The capital cost is a key component of investment selection, as it represents the initial investment of all the facilities for wastewater treatment (Ren & Liang 2017). The capital cost is estimated considering all construction and replacement processes for each alternative. Alternative C needs the highest capital costs because it introduces the advanced treatment process and upgrades the bioreactors to improve nitrogen removal. Alternative B needs the lowest capital costs because the capacity of bioreactors is increased by changing the existing primary sedimentation framework instead of constructing new bioreactors. The cost for alternative A is higher and lower than those of alternatives B and C, respectively, because the bioreactors are improved by introducing a four-stage BNR process and replacing the old equipment.

3.2.2. O&M costs

The O&M cost includes all costs for operating WWTPs, such as those of wastewater and sludge treatment, chemical production, energy consumption, and labor (Ren & Liang 2017). In this study, the factors influencing the O&M costs of each alternative were analyzed qualitatively because quantification involves notable uncertainties. The operational costs were described as high, medium, or low considering the factors leading to O&M cost fluctuations for each retrofitting alternative. Alternative A exhibits reduced energy consumption owing to the use of efficient blowers and pumps. In addition, the energy production from sludge resourcification is expected to increase because of the production of sludge pellet fuel and the improvement of the anaerobic digesters. Alternative B requires increased O&M costs because it treats more wastewater and involves the operation of Gould-type sludge collectors and a new bypass line in the primary sedimentation for ensuring a high concentration of MLSS. Alternative C requires additional energy and operational labor because of the advanced treatment process.

3.2.3. Improvement of bioreactors

This criterion indicates the performance and characteristics of the bioreactors. Alternative A changes the treatment technologies to a four-stage BNR because the existing MLE or AST technologies produce a large amount of waste sludge with a low nitrogen removal efficiency. Alternative B expands the capacity of the bioreactors by replacing several parts of the existing primary sedimentation systems with bioreactors. Furthermore, the MLSS concentration is increased to 4,000 mg/L. Alternative C changes several parts of the bioreactors for the MLE and AST processes to four-stage BNR to improve the nitrogen removal efficiency.

3.2.4. First flush treatment during the storm event

The treatment of the first flush rainwater is important as it has a high concentration of pollutants. WWTP Seo-Nam has been criticized because of untreated rainwater discharge. This criterion pertains to the treatment of the first flush rainwater influent, which is necessary because most of the collection systems in Seoul are combined sewer pipes and the existing systems cannot treat the pollutants in rainwater. The municipality has plans to construct rainwater treatment facilities with a capacity of 3,260,000 m^3/d. However, several groups are concerned about land occupation, budget, and excessive capacity of these facilities. To address this problem, each alternative involves different rainwater treatment facilities: The capacities for alternatives A, B, and C are 3,260,000, 1,360,000 , and 2,000,000 m^3/d, respectively. The experts were asked to identify the proper capacity.

3.2.5. Advanced treatment processes

Advanced treatment processes must be introduced to eliminate micro-plastic, synthetic musk compounds, EDCs, ARGs, and other pollutants to improve the quality of receiving water. Micro-pollutants such as HHCB, AHTN, and MK have been detected in the effluent from the WWTP. Although additional O&M costs and electricity are required to operate the advanced treatment process systems, the treatment of micro-pollutants can help enhance the effluent quality. Alternatives A and B do not have this process, but alternative C does.

3.2.6. Odor impact

The indicator of this criterion pertains to the factors affecting odor. In this study, odor was considered to be affected by the production of sludge and wastewater treatment. Less sludge production corresponds to less odor. Moreover, underground treatment processes are associated with reduced odor. The sludge production in alternatives A and C is reduced by the introduction of the four-stage BNR process. However, the odor impact is higher in alternative B because the biological technologies remain, and the capacity of the bioreactors is increased.

3.2.7. Recycling possibility

With growing interest in reusing treated wastewater to ensure sustainability, future WWTPs can be tasked with recycling resources from wastewater and sludge. The recycled resources may be treated water, energy, or materials from the treatment process. WWTP Seo-Nam adopts two main recycling strategies: (1) to recycle the treated water as gray water to Magok city. The effluent quality can be increased by the advanced treatment process in alternative C, resulting in a higher possibility of recycling the treated water; (2) to use sludge pellets as an energy source. Notably, the use of sludge pellet may lead to the generation of fine dust and odor.

3.2.8. Sludge disposal

Sustainable sludge disposal is a critical issue for WWTP Seo-Nam. At present, the dewatered sludge is disposed of via landfilling. However, the existing landfill sites may soon become unavailable because of the expiration of the contract with the adjacent city and little possibility of extending the contract. To ensure independent sludge disposal, incineration and drying facilities must be expanded or newly constructed. Alternative A constructs additional drying facilities. However, the sludge pellets generated by drying have several related issues, and thus, the incineration facilities are recommended to be expanded in alternatives B and C. Alternative B involves both incineration and drying facilities, whereas only incineration facilities are implemented in alternative C.

3.2.9. Energy independence

Energy independence is the ratio of energy consumption to production, both of which affect the intensity of indirect GHG emissions (Molinos-Senante *et al.* 2014). The energy independence ratio is the highest in alternative A because the energy consumption decreases, and the energy production increases. The energy consumption in alternatives B and C is higher than that in alternative A because of the expansion of the bioreactors and implementation of the advanced treatment process, respectively.

3.2.10. Effective land use

The effective land use criterion assesses the utilization of land in the WWTP not only in terms of providing local amenities to inhabitants, such as gyms, parking lots, and recreational parks, but also the construction of complex cultural spaces including department stores, research clusters, cinemas, or shopping centers. Because the WWTP is constructed underground, the existing WWTP site can be used for other applications. Alternatives A and C have similar levels of effective land use as alternative A is assumed to secure land for underground processes and alternative C involves the construction of complex cultural spaces and the introduction of advanced treatment systems to address both environmental and social issues. In contrast, alternative B uses the land only for improving the treatment performance, especially nitrogen removal, and thus, may not significantly change the existing land usage.

3.2.11. Public acceptance

Municipalities must alleviate the locally unwanted land use and NIMBY tendencies of the public (Huh *et al.* 2020). The public opinion must be considered in the planning step of the retrofitting alternatives. Alternative A can increase energy sufficiency, as mentioned by the municipality. However, alternative B may be more amenable to the public because the capacity shortage is a notable problem for both the municipality and the public. Alternative C reflects the public concern in terms of micro-pollutant treatment.

3.2.12. Willingness to pay tariff

The public must be willing to pay an increased tariff owing to the increased expenditure for upgrading the WWTP, and reasonable justifications for the increased tariff must be provided in advance. This criterion focuses on these reasons for different retrofitting alternatives and plans. The sewerage tariff must be increased within a reasonable range to be acceptable. The effluent quality increases in alternative C owing to the advanced treatment process, which may lead to increased sewerage tariff. In contrast, alternative A can balance the increase in the O&M costs because of its recycling strategy and reduced energy consumption. Alternative B involves only a slightly increased tariff to treat more wastewater.

3.3. Analysis of the weight of the evaluation criteria in the AHP

According to the analysis of the weight of the evaluation criteria by the AHP (Table 6), the environmental dimension is evaluated to be the most important (0.636), followed by economic (0.217) and social dimensions (0.147). Molinos-Senante *et al.* (2014) seemed the first to propose evaluation criteria for the social dimension in sustainability assessment, but its importance is lower than that of the environmental impact associated with large and old WWTPs, consistent with previous findings (Lizot *et al.* 2021).

The final weights of the capital costs and O&M costs are 0.081 and 0.137, respectively. The O&M cost of the economic dimension is 1.7 times more important than the capital cost, despite the budget being one of the most critical factors in

Table 6 | Final weights of evaluation criteria

Dimension	Weight	Evaluation criteria	Weight	Final weight	Rank
Economic	0.217	Capital cost	0.371	0.081	6
		O&M cost	0.629	0.137	2
Environmental	0.636	Improvement of biological reactors	0.107	0.068	7
		First flush treatment during the storm event	0.090	0.057	8
		Advanced treatment processes	0.083	0.053	11
		Odor impact	0.128	0.082	5
		Recycling possibility	0.129	0.082	4
		Sludge disposal	0.269	0.171	1
		Energy independence	0.194	0.123	3
Social	0.147	Effective land use	0.365	0.054	10
		Public acceptance	0.366	0.054	9
		Willingness to pay tariff	0.269	0.040	12

the planning steps of retrofitting projects. When evaluating the sustainability of retrofitting alternatives, one should focus on the prediction of fluctuations in the O&M costs after retrofitting.

The most important indicator in the environmental dimension is sludge disposal, with a final weight of 0.269. In general, the environmental dimension is particularly important in terms of sludge production and sludge disposal effect (Lizot *et al.* 2021). Sludge disposal in WWTP Seo-Nam is mainly based on landfilling or consignment to external facilities. The experts believe that independent methods of sludge disposal must be identified. The second-most important criterion in the environmental dimension is energy independence, with a weight of 0.194. This criterion has been frequently mentioned in the existing studies as having a high weight (Muga & Mihelcic 2008; Molinos-Senante *et al.* 2014; Plakas *et al.* 2016; Gherghel *et al.* 2020; Delanka-Pedige *et al.* 2021; Makan *et al.* 2021), likely because the energy consumption indicators are related with the emission of GHG or carbon footprint. The weights of the recycling possibility and odor impact are 0.128 and 0.129, respectively, corresponding to moderate ranks. Wastewater must be recycled for sustainable development; however, the associated criterion is ranked at the medium level because of the emphasis on sludge disposal and energy independence. The lowest weights pertain to bioreactor improvement (0.107), first flush treatment during storm events (0.090), and advanced treatment processes (0.083), which are focused on enhancing the effluent quality and quality of receiving water. Overall, sustainable requirements, such as those of energy, sludge, and recycling strategies, are assigned higher importance than the traditional goals of WWTPs such as the CEC removal. This finding must be interpreted with caution: The traditional functions of WWTPs are not insignificant, but retrofitting alternatives must focus on the specific challenges of WWTPs before the implementation of new regulations.

The weights of the criteria in the social dimension, i.e., the effective land use, public acceptance, and willingness to pay tariff, are 0.365, 0.366, and 0.269, respectively. Notably, criteria in the social dimension have been proposed recently, and their importance levels differ across experts. The questionnaire did not present clear consistency in the results of relative weighting. Effective land use and public acceptance are assigned higher importance than willingness to pay tariff. Considering the situation of Seoul City, the former criteria are important because of the scarcity of available lands and increased public participation in decision-making in the municipality. These results are also attributable to the increase in the sewerage tariff (Seoul 2018a). The final importance level of the evaluation criteria was determined by multiplying the dimension importance with the importance of the subcriteria (Table 6). Table 6 also represents the weight ranks. Sludge disposal is the most important criterion in retrofitting the WWTP because it relies mostly on landfilling and other methods such as incineration must be urgently incorporated. The O&M costs are the second-most important criterion. Novel requirements for sustainable WWTPs such as energy independence and recycling possibility appear at higher ranks than the requirements for traditional WWTPs such as treatment performance. Despite the growing importance of the social dimension in upgrading WWTPs (Huh *et al.* 2020), the corresponding criteria are not prominent in the selection of the retrofitting alternative for the Seo-Nam WWTP.

3.4. Comparison of the alternatives

Table 7 presents the normalized sustainability scores for each evaluation criterion. The final sustainability score of alternative A was 0.623, which was the highest among the three alternatives, followed closely by that of alternative C (0.612). Alternative B showed the lowest sustainability (0.426).

Alternative A received high scores in terms of sludge reduction and increased energy independence ratio owing to the upgrading of digesters, increased biogas production, and replacement of the existing systems such as blowers and pumps by energy-efficient equipment. Alternative A also received high scores in terms of energy recycling owing to sludge drying by-products. Alternative B received the lowest sustainability score. Although this alternative received high scores in the improvement of bioreactors as it expanded the capacity of the bioreactors, low scores were obtained in other evaluation criteria such as sludge disposal and energy independence. Furthermore, there are concerns about indiscriminately increasing the capacity at present, because the population is expected to decrease in the future. According to statistical analysis, the population in Seoul has been predicted to decrease post-2030, and the decrease may occur earlier because of COVID-19. Finally, alternative C received a high sustainability score of 0.612 as it can enhance the quality of treated water by introducing advanced treatment processes to eliminate microplastics and synthetic musk. This aspect earned the highest score in terms of public acceptance as the public has expressed growing concerns regarding micro-pollutants. Alternatives B and C focus on improving the water treatment function and effluent quality. Notably, alternative B is less sustainable than the

Table 7 | Normalization of the assessment results of alternatives and sustainability

		Score		
Evaluation criteria	**Weight**	**A**	**B**	**C**
Capital cost	0.081	0.632	0.536	0.560
O&M cost	0.137	0.642	0.571	0.511
Improvement of biological reactors	0.068	0.430	0.628	0.648
First flush treatment during the storm event	0.057	0.806	0.271	0.526
Advanced treatment processes	0.053	0.304	0.294	0.906
Odor impact	0.082	0.764	0.352	0.541
Recycling possibility	0.082	0.850	0.310	0.427
Sludge disposal	0.171	0.554	0.445	0.704
Energy independence	0.123	0.682	0.346	0.645
Effective land use	0.054	0.564	0.269	0.781
Public acceptance	0.054	0.325	0.512	0.795
Willingness to pay tariff	0.040	0.866	0.406	0.291
Total sustainability	–	**0.623**	**0.426**	**0.612**

alternative C because the expanded capacity may not be desirable in the future with the predicted population decreases. The O&M costs and tariff increase in alternative C. However, the environmental and social benefits such as sludge production, water recycling, and fulfillment of residents' needs can offset the increased costs.

4. CONCLUSIONS

This study presented several retrofitting alternatives for WWTP Seo-Nam in Seoul. Most of the existing sustainability assessments focus on the unit processes and operative performance measurement. In contrast, the proposed assessment system could appropriately evaluate the sustainability of the retrofitting plans. The alternatives aimed to address different environmental issues in the study area, such as energy efficiency, WWTP performance, stringent effluent quality requirements in the future, and independent sludge disposal. The proposed criteria focused on evaluating economic soundness, reduced environmental impacts, and improved social acceptability. AHP was performed to estimate the weights of each criterion, as this technique can consider the opinions of various stakeholders. The retrofitting alternatives were quantitatively evaluated, and the most sustainable alternative was identified. The proposed assessment model can support decision-making and allocation of resources by enabling the comparison of retrofitting plans.

The environmental dimension was assigned the highest importance (0.636), followed by the economic dimension (0.217) and the social dimension (0.147). The environmental dimension subcriteria of sludge disposal, energy independence, resource recovery of wastewater, and odor impact were assigned high importance, highlighting the need to use innovative methods to build sustainable WWTPs. Alternative A corresponded to the most sustainable system (0.623). The sludge disposal and energy independence of this alternative were superior to those of the alternatives. Alternative C ranked second (0.612). The concerns regarding increased sewerage charges to improve the quality of treated water were offset to a certain extent by the possibility of recycling treated water, improving the quality of life of residents, and using advanced treatment processes. Alternative B ranked the lowest (0.426). Although maintaining most components of the existing treatment system helped reduce the initial investment costs, WWTP Seo-Nam was considered to have increased operating costs and energy usage owing to the aging equipment, leading to reduced sustainability. Although alternatives B and C both focused on improving the effluent quality, alternative C was assigned a higher score owing to the higher perceived environmental benefits.

Because this assessment involved qualitative measurement for certain criteria such as those the social dimension, the results may vary across stakeholders. Furthermore, given the complexity of decision-making for large-scale, old WWTPs, most municipalities are reluctant to change the WWTP significantly and radically to avoid unpredictable results. Therefore, this study presented alternatives that did not replace the existing treatment system with radical innovations. Future studies can be focused on identifying other alternatives, such as the introduction of treatment technologies such as membrane bioreactor processes, anaerobic ammonium oxidation processes for main treatment, use of aerobic granules, and advanced oxidation processes.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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