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Techno-Economic Evaluation of Ozone Application to Reduce Sludge Production in Small Urban WWTPs

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Abstract: In Chile, small wastewater treatment plants (WWTPs) (treatment capacity of less than 4,800 m^3/d) are normally not designed with consideration for the potential valorization of generated sludge. For this reason, they are generally operated at high solids residence times (SRT) (15 d) to promote the decay of biomass, promoting less sludge production and reducing the costs associated with biomass management. Operation at high SRT implies the need for a larger activated sludge system, increasing capital costs. The implementation of a sludge-disintegration unit by ozonation in future WWTPs could enable operation at an SRT of 3 d, with low sludge generation. In this work, we evaluate how the implementation of a sludge-ozonation system in small WWTPs (200–4000 m^3/d) would affect treatment costs. Four scenarios were studied: (1) a current WWTP operated at an SRT of 15 d, without a sludge ozonation system; (2) a WWTP operated at an SRT of 15 d, with a sludge-ozonation system that would achieve zero sludge production; (3) a WWTP operated at an SRT of 3 d, with a sludge-ozonation system that would provide the same sludge production as scenario 1; (4) a WWTP operated at an SRT of 15 d, with a sludge-ozonation system that would achieve zero sludge production. Economic analysis shows that the treatment costs for scenarios 1 and 2 are similar, while a reduction in cost of up to 47% is obtained for scenarios 3 and 4.

Keywords: disintegration process; ozonation; sludge reduction; sludge retention time

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1. Introduction

The management of sewage sludge is an important issue for wastewater treatment systems. In fact, although the volume of sludge produced in urban WWTPs is around 1% of their influent flow, sludge management represents around 50–60% of the total operating costs of WWTPs [1,2]. To address this in a more sustainable manner, sewage-sludge management has evolved from an approach involving only treatment and disposal to one considering conversion into value-added products (i.e., bioenergy or biobased materials). The latter alternative has the potential to reduce the quantity of sludge that ultimately needs to be disposed of and can reduce overall operating costs [3,4]. However, this approach usually only represents a viable alternative for valorizing sewage sludge in WWTPs that serve a population equivalent (PE) greater than 24,000 (4800 m^3/d) [5].

In Chile, as in many Latin American countries, about 80% of urban cities have a PE less than 24,000 [6], and consequently, the number of small WWTP is significant [7]. Moreover, progressive population growth and consequent urbanization is expected to increase in the number of urban WWTPs and therefore the quantity of sewage sludge that will require proper management [7]. At present, 97% of the Chilean urban population is served by approximately 300 WWTPs, and around 62% of these plants have design capacities of less than 4800 m^3/d [6,7]. Around 60% of these WWTPs use activated sludge technology to remove organic matter from wastewater, generating about 345,000 dry tons per year that must be managed [7]. Operation of activated sludge systems at high SRT values (15 d) is the most used strategy for reducing sludge production in Chilean WWTPs. As SRT increases, the maintenance energy in bacterial metabolism increases, which leads to a reduction in sludge production [8–11]. A reduction of about 60% of excess sludge production can be achieved when SRT is increased from 2 to 18 days [12]. However, the operation of activated sludge systems with longer SRTs results in high operating costs associated with aeration required by aerobic biomass [9,12]. Additionally, this sludge-reduction strategy promotes the conversion of ammonium nitrogen into nitrate, as a result of a nitrification process, increasing the aeration requirements. Required energy consumption for conventional activated sludge WWTPs is between 0.14 and 0.16 kWh/m^3 and can increase to 0.65–2.28 kWh/m^3 when nitrification processes take place during biological wastewater treatment [9,13].

An alternative method to reduce sludge production in WWTPs is the application of in situ sludge-reduction technologies, such as ozonation, ultrasonic methods, alkaline treatment and thermal processes [2,14,15]. Until now, only ozonation and ultrasonic methods have been applied in full-scale urban WWTPs [16]. Ozonation promotes the disintegration and solubilization of biodegradable and non-biodegradable compounds in the sludge [17,18]. This process can be applied to a fraction of the sludge recycled from the secondary decanter to the biological reactor. In this case, ozonated sludge is returned to the biological reactor, where the biodegradable fraction of the hydrolyzed sludge is assimilated by active microorganisms. This procedure can generate a relevant net reduction in the amount of sludge that must be managed [10,12]. The ozone dosage is typically in the range of 0.01–0.74 g O_3/g total suspended solids (TSS), resulting in a sludge reduction of between 10% and 100% [16,17,19]. It is important to note that literature has reported that the ozone-dose range should be between 0.03 and 0.05 g O_3/g TSS to obtain an appropriate balance between sludge-reduction efficiency and operating costs [20,21].

The implementation of a sludge-ozonation system in existing small urban WWTPs (operated at an SRT of 15 d) would be economically feasible when sludge management (dewatering and disposal) costs are higher than the costs associated with ozonation-unit operation. These costs are the sum of the investment associated with required equipment and the increase in operating costs related to energy consumption for ozone production, as well as the additional aeration required to cope with the increase in chemical oxygen demand (COD) resulting from the ozonated sludge [10,15]. In the case of future small urban WWTPs, in addition to the aspects already mentioned, it should be considered that the implementation of a sludge-ozonation system would allow for the design of WWTPs to be operated at short SRTs (3 d) with a reduced sludge production. Additionally, operation at such low SRTs would allow for a reduction in investment costs associated with new WWTPs, mainly due to the lower volume required for both a biological reactor and secondary decanter. In this context, both sludge-minimization strategies have advantages and disadvantages when compared to one another, and there is no obviously superior sludge-reduction method for urban WWTPs with treatment capacities of less than 24,000 PE. For these reasons, this work is focused on studying the economic viability of the installation of sludge-ozonation systems in existing and future small WWTPs.

This work is intended to represent a contribution to existing literature by providing information that can be useful in the evaluation and implementation of potential of sludge-ozonation units as a way to reduce sludge production in small WWTPs. Previous studies have concentrated on the techno-economic evaluation of sludge-reduction technologies in the water line and/or sludge line of large WWTPs [2,15–17], while economic assessments of sludge-reduction strategies for small urban WWTPs have not been studied.

2. Materials and Methods

2.1. Description of Studied WWTP Configurations

Four scenarios for the treatment of urban wastewater in small cities are studied in this work:

- Scenario 1: This scenario is based on a conventional WWTPs that include preliminary treatment (i.e., screening and grit-removal units), followed by an activated sludge unit operated at an SRT of 15 days in order to remove organic matter from wastewater, as well as a tertiary treatment based on chlorination. Generated sludge is dewatered by means of a decanting centrifuge.
- Scenario 2: This scenario is similar to the first one, but a sludge-ozonation unit is implemented to obtain zero sludge production during wastewater treatment. With this alternative, a fraction of the mixed-liquor sludge is continuously transferred to the sludge-ozonation unit for disintegration and is then returned to the biological treatment system for biodegradation.
- Scenario 3: A WWTP is designed with an activated sludge system operated at an SRT of 3 days, combined with a sludge-ozonation unit to produce the same quantity of sludge as in the first scenario.
- Scenario 4: This scenario is similar to the third one, but in this case, the ozonation unit is designed to achieve zero sludge production, so decanting-centrifuge requirements are not considered.

For all studied scenarios, the dewatered sludge is disposed of in a landfill, without any valorization process. In this work, WWTPs with capacity to treat sewage from a population equivalent of between 1000 and 20,000 PE (between 200 and 4000 m^3/d) were studied.

2.2. Mass and Energy Balances

For the studied scenarios, mass and energy balances were performed considering typical operating conditions of WWTPs (Table 1). The total influent COD concentration was 500 mg/L (soluble biodegradable COD (S_S): 150 mg/L; soluble non-biodegradable COD (S_I): 50 mg/L; particulate biodegradable COD (X_S): 200 mg/L; particulate non-biodegradable COD (X_I): 100 mg/L). Mass and energy balances enabled determination of oxygen consumption, energy consumption, ozone consumption and sludge production, as well as sizing of the required unit for wastewater and sludge treatments (preliminary treatment, biological treatment, sludge ozonation, dewatering and chlorination). Operational conditions of wastewater and sludge treatment units were considered constant, i.e., assuming no daily or seasonal variations occur during the operation of WWTPs.

Table 1. Summary of values used to perform both mass and energy balances.

Unit Operation	Values
Mass balances	
Activated sludge process	Hydraulic retention time (HRT): 0.25 d Biomass concentration in aeration tank: 4 kg VSS/m^3 Biomass yield ($Y_{x/s}$): 0.43 kg VSS/kg $COD_{consumed}$ [22] Decay coefficient (k_d): 0.24 d^{-1} [22] Volatile suspended solids concentration in the effluent ($VSS_{effluent}$): 0.02 kg VSS/m^3 Non-biodegradable fraction of heterotrophic biomass (X_P/X_H): 0.15 [22] 1.42 kg COD/kg VSS for X_P and X_H [22] 1.55 kg COD/kg VSS for X_I COD fraction [23] Oxygen requirement for ammonium oxidation: 4.57 kg O_2/kg N [22]
Ozonation unit	X_H, X_I and X_P were solubilized into S_S
Sludge dewatering	25% dry matter TSS/VSS ratio: 0.75 kg/kg
Energy balances	
Wastewater influent pumping	0.0385 kWh/$m^3_{influent}$ [22]
Screens	0.0004 kWh/$m^3_{influent}$ [22]
Grit removal	0.008 kWh/$m^3_{influent}$ [22]
Aeration	1 kWh/kg O_2 [22]
Chlorination	0.00055 kWh/$m^3_{influent}$ [22]
Sludge pumping	0.01 kWh/$m^3_{influent}$ [22]
Centrifuge	0.3 kWh/kg TSS [24]
Ozone generation	15 kWh/kg O_3 [25]

TSS and VSS are the concentration of total suspended solids and volatile suspended solids, respectively; and X_H and X_P are the concentration of heterotrophic biomass concentration and endogenous residues from decay, respectively.

For scenario 1, the daily amount of sludge produced from the activated sludge unit was calculated according to the methodology described by Crutchik et al. (2020) [26]. In the case of scenarios 2, 3 and 4, where the activated sludge system was combined with a sludge-ozonation system (Figure 1), sludge generation (kg TSS/d) was calculated using Equations (1) to (5).

$$Produced\ sludge = \frac{(VSS_{XIr} + VSS_{XPr} + VSS_{XHr})}{0.75} \times Q_0 \times HRT \times \left(\frac{1}{SRT} - \alpha \times \beta\right) \quad (1)$$

$$VSS_{XIr} = \frac{X_{I0} \times SRT}{HRT \times 1.55} \quad (2)$$

$$VSS_{XPr} = k_d \times 0.15 \times X_{Hr} \times SRT \quad (3)$$

$$VSS_{XPr} = \frac{\frac{(S_{s0}+X_{s0}) \times Y_{x/s}}{1+k_d \times SRT}}{\frac{HRT}{SRT} + Y_{x/s} \times \frac{Q_{ozonated\ sludge}}{Q_0} \times \frac{\alpha \times (1-0.15)}{1+k_d \times SRT}} \quad (4)$$

$$\beta = \frac{Q_{ozonated\ sludge}}{V_R} \quad (5)$$

where VSS_{XIr}, VSS_{XPr} and VSS_{XHr} are the concentration of VSS inside the reactor associated to X_I, X_P and X_H, respectively (kg/m^3); Q_0 is the inlet flow rate (m^3/d); $Q_{ozonated\ sludge}$ is the inlet flow rate of the sludge-ozonation system (m^3/d); V_R is the volume of the aeration tank (m^3); α is the fraction of sludge that was solubilized during ozonation; and β is the amount of daily ozonated sludge with regard to the total amount of sludge in the activated sludge unit. In this work, a specific ozonation dosage (SOD) was set at 0.03 kg O_3/kg TSS [27], resulting in a sludge-solubilization degree of 25% (α) [27]. According to Equation (1), once the SOD is fixed and therefore the solubilization sludge degree is established, the amount of generated sludge can be controlled by manipulation of the fraction of daily ozonated sludge (β).

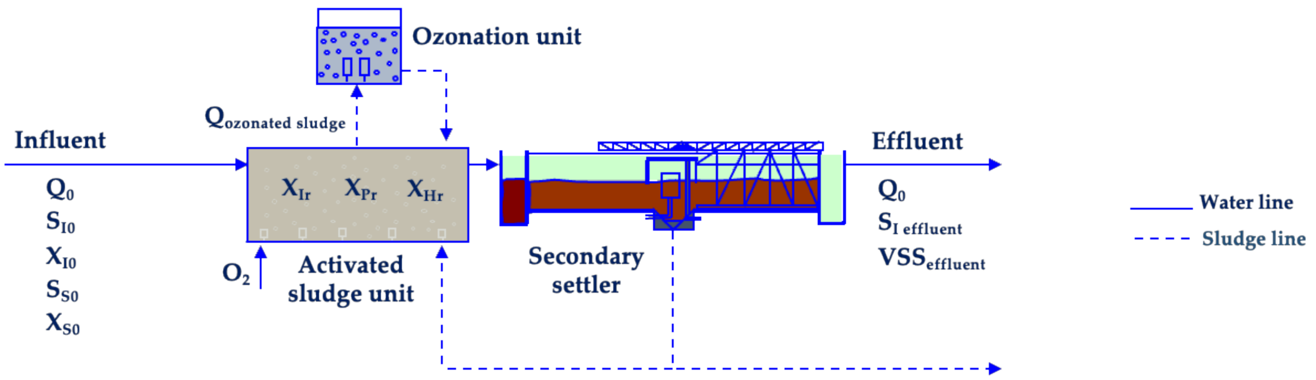

Figure 1. Schematic layout of the activated sludge system combined with an sludge-ozonation unit.

2.3. Methodology for Economic Assessment

Economic analysis of wastewater treatment for the studied scenarios was carried out considering total capital costs, as well as operating and maintenance (O&M) costs of the WWTP. Total capital costs, as well as operating and maintenance costs for treatment units are detailed below:

(a) Total capital costs include those related to the purchase of main equipment (preliminary treatment, activated sludge system, sludge-ozonation, sludge-dewatering and chlorination units) and for required for piping, instrumentation/electricity, engineering costs and civil work. The ozonation unit involved the incorporation of an ozone generator includes an ozonation tank and two pumps. Equipment capital costs were calculated based on the data and cost functions reported in studies found in the literature [28–30]. Costs related to the required equipment for piping, instrumentation/electricity, engineering costs and civil work were estimated as 15%, 25%, 10%, 34%, and 12% of total equipment costs, respectively.

(b) Operating and maintenance costs include energy consumption (due to mixing and pumping, oxygen requirements for biological treatment system, sludge dewatering and ozonation generation), reagents, labor and maintenance. Energy consumption related to the ozonation unit includes the cost of oxygen supply, the energy requirement for the production of ozone and pumping of ozonated sludge. Energy consumption was corrected based on the WWTP size, taking into account results obtained by Trapote et al. (2014) [31]. The price of electricity used was USD 0.095 /kWh [32], and costs associated with sludge disposal were calculated as USD 100 /Ton [33]. The amount of reagents needed for the sludge-dewatering (polyelectrolytes: USD 2/kg) and chlorination processes (sodium hypochlorite: USD 0.52 /kg) was calculated, taking into account a dose of 5 g/kg TSS [22] and 5.1 mg/L, respectively. Maintenance costs were calculated as fixed percentages of the capital cost (1%). The labor cost of operators was assumed to be USD 5.45 /person hour.

The minimum cost of wastewater treatment (USD/m^3) was estimated as the value that results in a net present value (NPV) of zero (Equation (6)):

$$NPV = \sum_{t=1}^{T} \frac{C_t \times (1+i)^t}{(1+r)^t} - total\ capital\ costs \tag{6}$$

where C_t is the sum of the operating and maintenance costs, *i* is the inflation rate (3%), *r* is the interest rate (5%) and *T* is the payback time (20 years).

Uncertainty and variability can be present in the input variables used in economic analysis. Therefore, a sensitivity analysis was carried out. For this purpose, two economic parameters (price of energy and sludge-management costs) were considered. A range of ± 15% was considered for each parameter.

3. Results and Discussion

3.1. Effects of Sludge Ozonation on Sludge Production and Energy Consumption

Sludge-mass balance was applied to a WWTP with a sludge-ozonation system in order to determine how the fraction of daily ozonated sludge (β) affects sludge production (Figure 2A). The operation of the WWTP without ozone application was used as baseline to calculate the reduction in sludge production. As can be observed in Figure 2A, when a certain SOD (kg O_3/kg TSS) is applied in the ozonation tank, the reduction in sludge production depends linearly on the fraction of daily ozonated sludge. Therefore, the degree of sludge reduction does not depend on the applied SOD, as is generally reported in the literature [10]. Instead, it depends on the product of the applied SOD and the fraction of daily ozonated sludge, i.e., the daily amount of applied ozone per mass of solids (kg O_3/kg TSS·d) [34]. The SRT applied in the activated sludge system is another factor that affects sludge reduction (Figure 2A). An increase in SRT promotes biomass decay, and therefore, less sludge is generated compared to systems operated at low SRT. This implies that an increase in SRT in the activated sludge system will produce a reduction in the amount of ozone required to obtain a given reduction in sludge production. In fact, when a given SOD is applied to the sludge, the observed biomass yield coefficient (g $SS_{generated}$/g $COD_{removed}$) is lower than that of an activated sludge system operated at a higher SRT [35]. Generally, the literature provides values of both SOD and percentage of sludge reduction. However, there is insufficient attention given to the daily fraction of ozonated sludge and the SRT. This could explain the discrepancies in sludge reduction reported for similar values of SOD [10,21]. In some works, the flow rate of returned ozonated sludge is provided, but these data alone do not allow for calculation of the daily fraction of ozonated sludge [17,36]. As a consequence, the obtained results cannot be extrapolated to other operating conditions.

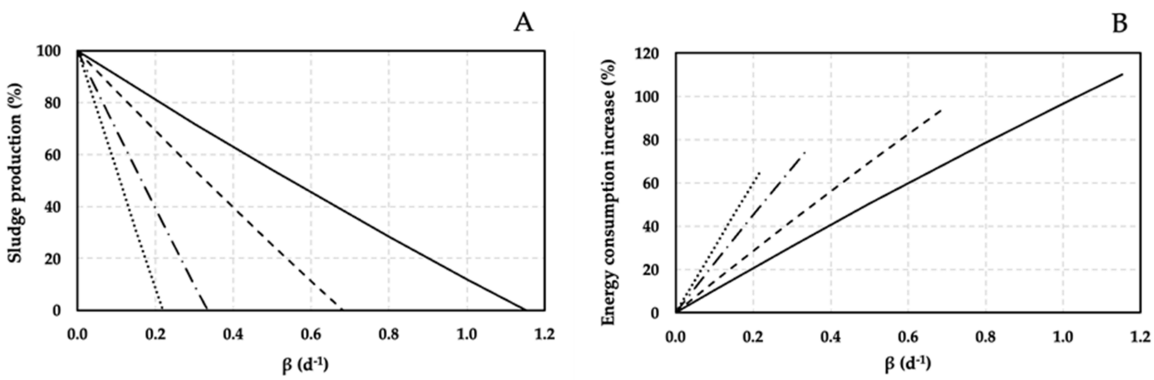

Figure 2. Effect of daily fraction of ozonated sludge (β) on (**A**) sludge production and (**B**) increase in energy consumption (SRT: —— 3 d; ----- 5 d; —·— 10 d; ······ 15 d). An ozone dose of 0.03 kg O_3/kg TSS, resulting in a sludge solubilization of 25% was used for calculations [26].

The specific daily ozone dose (kg O_3/kg TSS·d) applied to the sludge depends on both the SOD and the daily fraction of ozonated sludge. Therefore, a given specific daily ozone dose could be applied by supplying a high-SOD to a low daily fraction of ozonated sludge, or vice versa. This second strategy is preferable, since the application of a high SOD (>0.05 g O_3/g TSS) promotes a preferable reaction with dissolved organic matter and/or radical scavengers released from the sludge instead of solids [37–39]. This entails an inefficient use of the ozone to achieve a reduction in excess sludge production [19], which is not economically feasible [40]. In this work, the application of a low SOD (0.03 g O_3/g TSS) was proposed in order to favor disintegration of solids so that the amount of generated excess sludge could be controlled by changing the daily fraction of reactor sludge subjected to the solubilization process. This operating strategy has already been applied by Yasui and Shibata [41] and Yasui et al. [42], who found a linear reduction in the production of excess sludge in a pilot plant, as well as a reduction in the daily fraction of reactor sludge subjected to an SOD of 0.05 g O_3/g TSS. These authors observed that for different SRTs, zero excess sludge production could be achieved by changing the daily fraction of reactor sludge subjected to ozonation. This would confirm the results obtained in the present work, i.e., that there is a linear relationship between β and reduction in excess sludge production and that, furthermore, for a given SRT, the value of β can be adjusted such that zero sludge production is achieved.

The quality of sludge in terms of COD-type composition (fractions of X_H, X_p and X_I) also affects the degree of solubilization obtained for a given daily specific ozone dose and therefore the percentage of sludge reduction. It is expected that sludges containing a high fraction of X_H would be hydrolyzed easier than those with a high predominance of X_p and X_I fractions. Therefore, the operation of WWTPs at low SRTs would generate sludge requiring a lower ozone dose to be solubilized. However, the few studies that have investigated this topic show contradictory results [43,44]. For this reason, in this work, the solubilization degree was considered constant, independent of the sludge age.

Another parameter that could explain the discrepancy in results found in the literature when ozone is applied to reduce sludge production at full scale WWTPs is the ozone mass-transfer efficiency to the bulk liquid [45], which depends on several operating variables, such as gas flow rate, TSS concentration and ozone concentration [46–48]. These parameters are the key to improving the efficiency of the ozonation process and therefore to decreasing operating and capital costs associated with sludge reduction. For this reason, the obtained results should be expressed as a function of the amount of transferred ozone rather than the amount of applied ozone [34].

In the model used to carry out mass balance, it was assumed that all organic matter solubilized by ozone was biodegradable. This assumption was based on previous results reported by Boehler and Siegrist (2006) [35], who observed that 90% of solubilized organic matter in ozonated sludge was biodegradable. This fact is also supported by results provided by Gardoni et al. (2011) [36] and Torregrossa et al. (2012) [49]. They found that the effluent quality of WWTPs where ozone was used to promote sludge lysis hardly changed in terms of organic-matter concentration. This implies that the application of ozone increases oxygen consumption of the WWTP for two reasons: (a) the promotion of heterotrophic biomass lysis, which releases particulate biodegradable organic matter (*Xs*) contained within bacteria to the bulk liquid; and (b) the lysis of the non-biodegradable particulate fractions of organic matter (*Xi* and *Xp*), which allows them to be converted into a biodegradable carbon source for bacteria. As can be observed in Figure 2B, the application of ozone to promote sludge lysis has a greater impact on the energy consumption of WWTPs when they are operated at a low SRT. Basically, this is because operation at low SRT values promotes the conversion of biodegradable organic matter into biomass, which implies high sludge production and a low aeration requirement (low energy consumption) compared to WWTPs operated at high SRTs. Therefore, more ozone and "extra aeration" are needed to solubilize and oxidize the sludge generated when the WWTPs are operated under low-SRT conditions.

3.2. Economic Impact of Sludge Ozonation on Treatment Costs

Capital and O&M costs were calculated for each studied scenario and for different WWTP capacities (Figure 3). The implementation of a sludge-ozonation unit in an existing WWTP that operates at an SRT of 15 days implies an increase of 0.5–1.2% in capital costs (Scenarios 1 and 2, Figure 3A) and a decrease in O&M costs of 0.1–5.2% (Figure 3B), resulting in a reduction in sludge production to zero. The overall economic evaluation, considering both capital and O&M costs, shows that the treatment costs of scenarios 1 and 2 are almost the same. That is, the cost saving related to sludge management and the extra capital and O&M costs of sludge ozonation are similar under the current sludge-disposal and energy costs (Figure 4). Of course, the convenience of reducing sludge production by means of ozonation strongly depends on the sludge-disposal taxes of each country. For example, in countries with high sludge-disposal taxes, reduced sludge production by ozonation is an economically viable strategy [17,35]. Even in cases where treatment costs are similar, the achievement of zero sludge production by ozonation could be an interesting operating strategy, since sludge-disposal regulations could change over time, and sludge disposal in landfills or agricultural applications of sludge could be restricted.

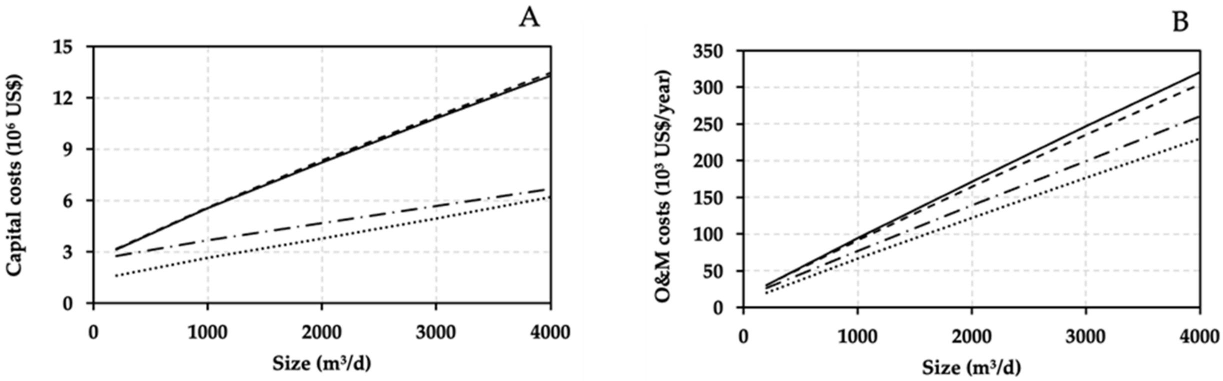

Figure 3. Capital (**A**) and O&M (**B**) costs estimated for each scenario and for WWTPs of different sizes (—— Scenario 1; ----- Scenario 2; —·— Scenario 3; ······ Scenario 4).

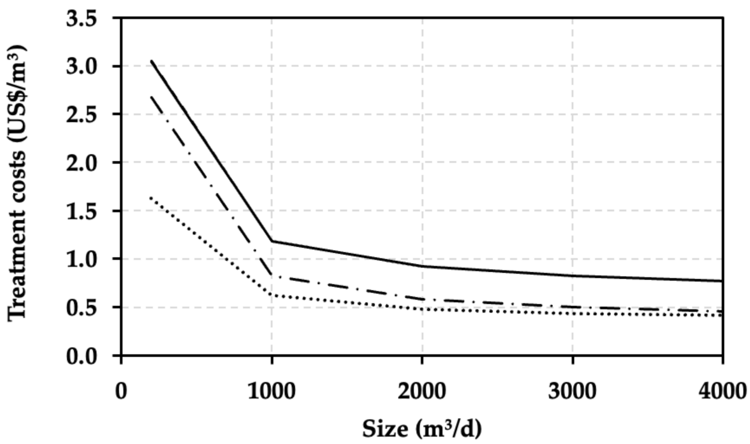

Figure 4. Treatment costs estimated for each scenario and for WWTPs of different sizes (—— Scenario 1; ----- Scenario 2; —·— Scenario 3; ······ Scenario 4).

Moreover, scenario 3 consisted of a WWTP designed to operate at an SRT of 3 days, including an ozonation unit to reduce sludge production to such values as those obtained when WWTPs are operated at an SRT of 15 (Scenario 1). Therefore, sludge production for scenarios 1 and 3 are similar. Scenario 3 would see a reduction in both capital (12.3–19.1%) and operating costs (11.9–49.7%) compared to scenario 1 (Figure 3A,B), leading to a significant decrease in treatment costs (Figure 4). The reduction in capital costs is mainly due to the reduced volumes of the activated sludge reactor and the secondary decanter. On the other hand, the reduction in operating costs is mainly attributed to aeration requirements, since the nitrification process does not take place when WWTPs are operated at an SRT of 3 d. This process increases the energy consumed by activated sludge systems by about 70% compared to activated sludge systems in which only organic matter is removed [9].

Treatment costs could be minimized if the WWTP is designed to operate at an SRT of 3 days with zero sludge production (Scenario 4, Figure 4). This scenario is especially advantageous in the case of WWTPs with the lowest studied treatment capacity, since a dewatering centrifuge would be no longer needed, generating relevant savings in capital costs (Figure 3A). As treatment capacity increases, these cost saving offset by the need for ozonation units with a higher capacity. As a result, the treatment costs for scenarios 3 and 4 tend to match.

Scenarios 3 and 4, where WWTPs are operated at an SRT of 3 days, provide the lowest treatment costs. This results from their low capital costs in comparison to WWTPs operated at an SRT of 15 days and their lower operating costs derived from the absence of nitrification and therefore the oxygen requirement associated with that process. In the case of scenario 4, the treatment costs are around 47% lower than those of scenario 1 for all the WWTP capacities studied in this work.

Sensitivity analysis shows that the operating costs of scenarios 1 and 3 present similar variations (around 3.4–4.1%) for changes of 15% in the prices of both sludge disposal and energy (Figure 5A,C). Logically, the operating costs of scenarios 2 and 4 do not depend on sludge-disposal price, while changes of 15% in energy prices cause variations of 7.2 and 7.0%, respectively (Figure 5B,D).

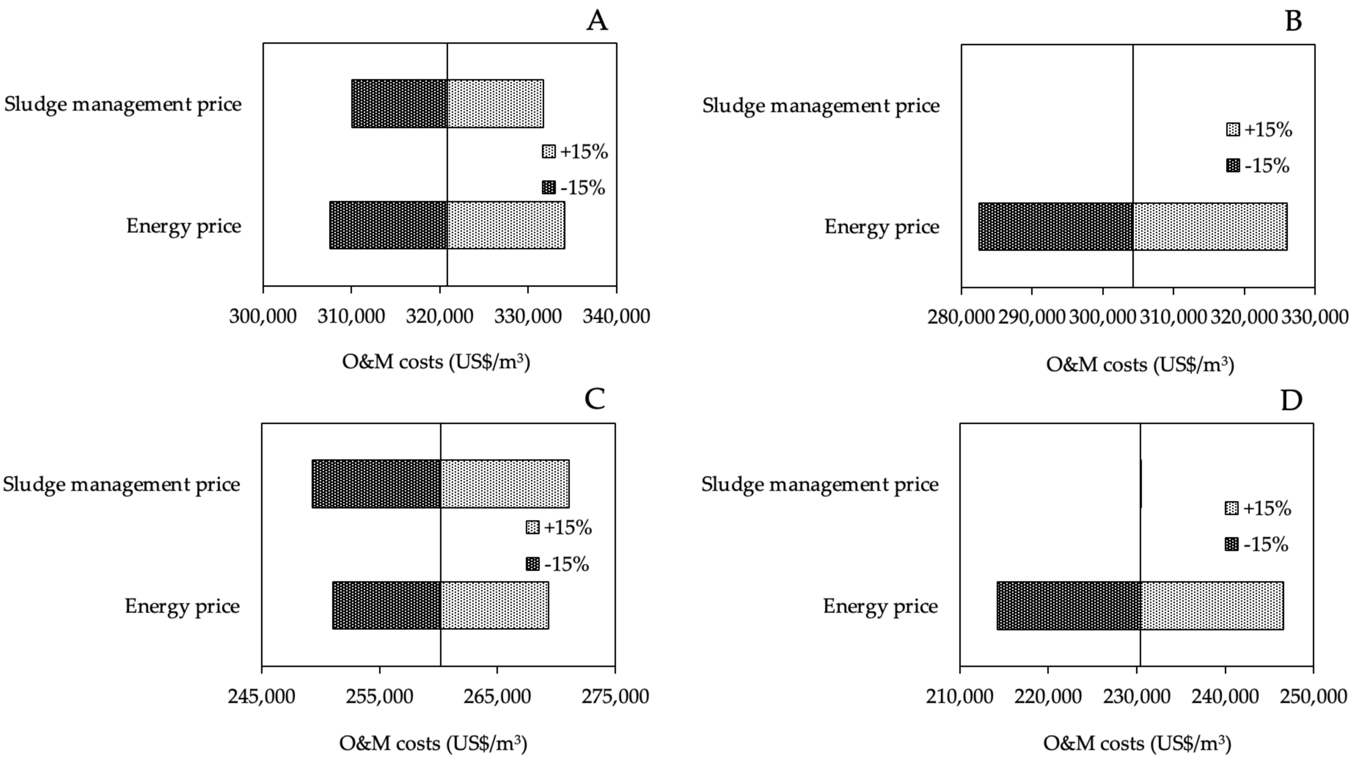

Figure 5. Sensitivity analysis for (**A**) Scenario 1; (**B**) Scenario 2; (**C**) Scenario 3 and (**D**) Scenario 4.

The economic feasibility of reducing sludge production through ozonation depends mainly on the cost of sludge management, as well as capital and operating costs associated with the installation of an ozonation system. To reduce the cost of the last two factors, it is necessary that the ratio of g $TSS_{hydrolyzed}$/g $O_{3applied}$ be as high as possible in order to minimize the capacity of the ozone generator and resultant ozone consumption. In this sense, in applications carried out at an industrial level, specific doses of ozone less than 0.05 g O_3/g TSS are applied [17,36,50] since they optimize the ratio of g $TSS_{hydrolyzed}$/g $O_{3applied}$. However, factors such as ozone concentration used during the sludge-hydrolysis process [46] or the efficiency of O_3 transfer to the liquid phase [10,18] are still poorly studied, and their optimization could improve the economics of the process. On the other hand, the ozone required to hydrolyze a given amount of secondary sludge depends on its composition, which could be determined based on its COD fractions (X_H, X_P and X_I) [43]. These fractions depend on both the characteristics of the wastewater and the SRT imposed in the activated sludge system. Therefore, a deeper understanding of how the hydrolysis of each of the COD fractions occurs is needed in order to determine the amount of O_3 required in each case. Hydrolysis of the sludge by ozonation could cause a worsening of the effluent quality. The literature agrees that the implementation of sludge-ozonation systems in WWTPs does not significantly influence the concentration of COD and SS In their effluent [10], although contradictory results have been reported regarding the concentration of nitrogen compounds [17,51]. According to Isazadeh et al. [52], the efficiency of N removal in WWTPs depends more on operating conditions than on the presence of an ozonation system. Therefore, when nitrogenous compounds must be removed from wastewater to satisfy discharge regulations, it is necessary to define the operating conditions of the WWTP that would allow a compromise to be reached between minimizing excess sludge production and obtaining a suitable effluent quality.

Currently, the operation of WWTPs is focused on recovering resources from wastewater in order to minimize the environmental impact associated with wastewater treatment. In this sense, the use of sludge generated in agriculture, instead of its disintegration through ozonation, could have a beneficial environmental impact due to the reduced use of chemical fertilizers. In addition, it must be considered that for a given SRT, the implementation of an ozone-disintegration unit will imply greater energy consumption by a WWTP, associated with both the generation of ozone and an increased aeration requirement. Therefore, not only the techno-economic aspects associated with sludge ozonation should be taken into account but also its environmental impacts, as it has already been done in the case of sludge hydrolysis prior to anaerobic digestion [53].

4. Conclusions

In WWTPs where a sludge-ozonation system is implemented, the reduction in sludge generation and the increase energy consumption depend not only on the specific ozone dose supplied (kg O_3/kg TSS) but also on the daily fraction of sludge ozonated, as well as the SRT applied in the activated sludge reactor. For a fixed daily specific ozone dose (kg O_3/kg TSS·d), the reduction in sludge generation and the increase in energy consumption is less with an increased SRT.

In the case of Chile, the implementation of sludge-ozonation systems in existing small WWTPs operated at an SRT of 15 d would not provide a reduction in treatment costs, since savings related to sludge management are offset by the necessary investment costs, as well as the increase in energy consumption. However, if a sludge-ozonation system is considered in the design of a new WWTP, operation at an SRT of 3 d could be considered, which would provide lower sludge production. This would result in an important decrease in capital costs, which would have a considerable impact on treatment costs.

In any case, the implementation of a sludge-ozonation system would not have a negative impact on treatment costs. Additionally, the operation of WWTPs would not be affected by future changes to sludge-management regulations.

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