Benefits of primary filtration systems in the downstream biological treatment of overloaded wastewater treatment plants (WWTPs)

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Abstract

Increasing hydraulic and organic overloading has intensified upgrading pressures on municipal wastewater treatment plants (WWTPs). Rising energy costs and stricter regulatory requirements further constrain reliance on conventional biological reactor expansion strategies. This study evaluates primary filtration applied upstream of activated sludge processes using a steady-state mass and energy balance modelling approach. The assessment examines microsieving and a combined microsieving-sand filtration configuration applied to overloaded WWTPs. Two representative operational scenarios are considered in the analysis. These correspond to average influent flow rates of 10,000 and 15,000 m^3/d under extended aeration conditions. A comprehensive steady-state mass and energy balance framework was applied. This framework quantifies changes in aeration tank volume, oxygen demand, aeration energy consumption, and secondary sludge production. Microsieving alone achieved aeration energy reductions ranging from 9% to 27%. The combined microsieving-sand filtration configuration enabled aeration energy reductions of up to 54%. Aeration tank volume requirements were reduced by 15-55%, depending on influent loading and filtration performance. Secondary sludge production decreased substantially, while primary sieved solids (PSS) with high dry solids content enhanced anaerobic digestion potential. For severely overloaded systems failing to comply with Directive (EU) 2024/3019, primary filtration restored effluent quality compliance without biological reactor expansion. Overall, primary filtration emerges as a space-efficient upgrading strategy aligned with European energy-neutrality objectives.

1. Introduction

Municipal wastewater treatment plants (WWTPs) are designed to remove organic matter, suspended solids, and nutrients from wastewater to protect receiving water bodies and public health (Bertrand et al., 2015). Over recent decades, rapid population growth, urbanization, and economic development have exerted increasing pressure on available water resources, intensifying the need for efficient wastewater treatment and reuse within sustainable water management frameworks (Abdelfattah et al., 2023). Under these evolving conditions, WWTPs are simultaneously required to comply with stricter effluent quality standards, while treating progressively higher hydraulic and organic loads. This combination has led to a marked increase in energy demand, positioning energy consumption as a critical operational and economic challenge for wastewater utilities worldwide (Capodaglio and Olsson, 2019; Siatou et al., 2020). In Greece, as in many European countries, municipal wastewater treatment relies predominantly on activated sludge processes as the core biological treatment technology. Due to this reliance, aeration tanks constitute the dominant energy consumers in most municipal WWTPs. Consequently, overall plant energy performance is highly sensitive to loading conditions and aeration requirements. A survey of seventeen Greek activated sludge WWTPs reported specific energy consumptions ranging from 0.13 to 2.28 kWh/m^3 for average daily flows between 300 and 27,000 m^3/d demonstrating both the magnitude and variability of energy demand across installations (Siatou et al., 2020). Many of these WWTPs were constructed several decades ago based on historical design assumptions. Since then, sewer network expansion, population growth, and continuously increasing influent flows have resulted in widespread hydraulic and organic overloading. Such operating conditions frequently lead to deteriorated treatment performance and reduced process stability. As a result, operational costs increase, while overall treatment efficiency declines (Prochaska and Zouboulis, 2020). Conventional upgrading strategies typically focus on aeration tank expansion or the incorporation of primary sedimentation as load-reduction measures (Tsamoutsoglou et al., 2022). However, biological reactor enlargement is often constrained by limited space availability and high capital costs in urban and peri-urban settings. Conventional primary sedimentation also requires large footprints and long hydraulic retention times (HRT). Moreover, primary sedimentation produces dilute primary sludges that increase downstream thickening, dewatering, and handling demands, further burdening plant operation (Caliskaner and Pena-Tijerina, 2019). These technical limitations have become increasingly significant in the context of rising energy prices and growing concerns over greenhouse gas (GHG) emissions. The European regulatory framework for urban wastewater treatment was historically established by Directive 91/271/EEC. This framework has recently been revised through the recast Urban Wastewater Treatment Directive, adopted as Directive (EU) 2024/3019, which introduces stricter treatment requirements and energy neutrality targets for wastewater treatment plants serving more than 10,000 population equivalents (PE) by 2040. This development intensifies the need for treatment strategies that reduce organic and solids loading, thereby improving the overall efficiency and energy performance of WWTPs. Conventional primary sedimentation, however, exhibits inherent performance limitations under modern operating conditions. Typical removal efficiencies rarely exceed 50-60% for total suspended solids (TSS) and 25-35% for biochemical oxygen demand (BOD_5), while performance remains highly sensitive to hydraulic loading variations common in tourist regions and combined sewer systems (Metcalf and Eddy, 1991; Lema and Martínez, 2017). During peak flow events, reduced sedimentation efficiency allows increased particulate organic matter to enter downstream biological processes. This, in turn, increases oxygen demand, biomass growth, sludge production, and overall energy consumption in activated sludge systems, exacerbating operational challenges in overloaded plants (Brown, 1987). Consequently, conventional primary sedimentation alone is increasingly regarded as insufficient to simultaneously address overloading, energy efficiency, and regulatory compliance. Many WWTPs operate under overloaded conditions, mainly due to high hydraulic loading. In such cases, expansion of the activated sludge process is often necessary. However, in many existing facilities, the available space is limited, which restricts further expansion and creates the need for compact upgrading solutions (Tsamoutsoglou et al., 2022). Microsieves, apart from their high efficiency in suspended solids removal, have a very small footprint, requiring about one-tenth of the area of conventional primary clarifiers. In addition, particle removal, sludge thickening and dewatering can be combined in a single unit, making microsieves a practical option for modern wastewater treatment plants (Turovskiy and Mathai, 2006). In this context, advanced primary treatment technologies have emerged as promising alternatives capable of effectively removing suspended solids and particulate organic matter directly from raw wastewater (Tchobanoglous et al., 2014). Micro- and nanoplastics (MNPLs) are increasingly detected in wastewater streams, while WWTPs represent the last barrier limiting their release to receiving waters (Gupta et al., 2026). These particles frequently associate with suspended solids and can therefore be removed together with particulate matter during primary filtration processes such as microsieving. Removing solids prior to the aeration tank limits the amount of particulate organic material entering the biological treatment units and prevents a portion of the associated MNPLs from reaching the aeration tank (Bayo et al., 2020). At the same time, capturing MNPLs during primary treatment reduces the likelihood that they will appear in the final effluent (Alatabe et al., 2025). Enhanced solids removal at the primary stage substantially reduces organic loading to biological treatment, resulting in lower aeration requirements, reduced sludge production, and decreased overall energy consumption (Blanca et al., 2000; Lema and Martínez, 2017). Among these technologies, microsieving has received particular attention as a compact, gravity-driven process requiring no chemical addition and minimal energy input while achieving high suspended solids removal efficiencies (Bourgeous et al., 2003; Grabbe et al., 1998; Wilén et al., 2012). By reducing particulate and organic loading to the activated sludge process, microsieving increases treatment capacity and lowers aeration energy demand (Sutton et al., 2008). Integrating microsieving with continuous sand filtration further enhances fine particulate removal. Compared with conventional primary sedimentation, this configuration requires a smaller footprint, lower capital and operating costs, and produces primary solids with substantially higher dry solids content. Advanced primary filtration has not yet been comprehensively assessed as an upgrading strategy for hydraulically and organically overloaded municipal WWTPs. Although most available studies focus on (Gikas, 2017; Venditto et al., 2020; Boutros et al., 2022; Tsamoutsoglou et al., 2024) individual filtration technologies and report removal efficiencies in terms of TSS and COD, they do not provide a quantitative link between upstream removal of particulate and biodegradable organic matter and overall plant performance. Specifically, the effects on aeration energy demand, activated sludge reactor volume requirements, and secondary sludge production under extended aeration conditions remain largely unexplored. As a result, the extent to which enhanced primary filtration could effectively replace conventional biological reactor expansion remains insufficiently understood. In this study, advanced primary filtration is evaluated as an integrated upgrading option for WWTPs operating under extended aeration, focusing on microsieving and a combined microsieving-sand filtration configuration installed upstream of the activated sludge process, under two representative operating scenarios corresponding to average influent flow rates of 10,000 and 15,000 m^3/d. Using a steady-state mass and energy balance approach, the effects of upstream removal of suspended solids and BOD_5 on oxygen demand, aeration energy consumption, aeration tank volume requirements, and secondary sludge production are quantified. The innovation lies in the early removal of suspended solids prior to the aeration tank, leading to reduced energy aeration requirements and increased treatment capacity without any need for expansion or modification of the biological treatment system. Under the examined assumptions and operating conditions, this approach has the potential to support compliance with the requirements of Directive (EU) 2024/3019 through upstream solids and load management.

2. Methodology and steady-state modelling framework

Section 2 presents the methodological framework adopted in this study. The detailed description of the modelling approach and the evaluated treatment scenarios is provided in the following subsections. The methodology is based on steady-state mass and energy balance calculations applied to activated sludge systems in order to assess the potential benefits of implementing primary filtration upstream of the biological treatment stage.

2.1 Methodological framework

This study aims to quantify the benefits derived from the implementation of primary filtration systems upstream of the biological treatment stage in hydraulically and organically overloaded WWTPs. Two representative treatment scenarios are developed in order to evaluate the impact of microsieving and combined microsieving-sand filtration on the performance of activated sludge systems operating under extended aeration conditions. The first scenario represents a moderately overloaded WWTP with an average daily influent flow rate of 10,000 m^3/d, which complies with the effluent discharge limits of Directive (EU) 2024/3019. The second scenario represents a severely overloaded WWTP with an average daily influent flow rate of 15,000 m^3/d, which fails to meet the effluent quality requirements of the same Directive under baseline operating conditions. The benefits of primary filtration are quantified in terms of reductions in aeration tank volume, oxygen demand, specific aeration energy consumption, and secondary sludge production. These performance indicators are calculated for two upgrading configurations: (i) microsieving as a standalone primary treatment step and (ii) a combined treatment configuration consisting of microsieving followed by sand filtration. Although microsieving and filtration technologies are individually investigated in previous studies, their systematic assessment as integrated upstream load-management strategies for overloaded municipal WWTPs remains limited. The novelty of the present work lies in the combined evaluation of microsieving and microsieving-sand filtration as quantitative upgrading solutions, explicitly linked to aeration energy demand, reactor sizing, sludge production, regulatory compliance, and energy-neutrality objectives. All mass and energy balance calculations were implemented using a spreadsheet-based calculation framework (Microsoft Excel). The framework applies standard steady-state design equations for activated sludge systems and ensures consistent treatment of all evaluated scenarios and upgrading configurations.

2.2 Description of the evaluated treatment scenarios

Two realistic wastewater treatment scenarios are defined, representing municipal WWTPs operating under Mediterranean conditions. The scenarios differ in terms of influent flow rate and baseline effluent quality performance. Scenario 1 corresponds to an overloaded WWTP treating an average daily influent flow of 10,000 m^3/d, which meets the effluent discharge limits of Directive (EU) 2024/3019 under baseline operation. Scenario 2 corresponds to a more severely overloaded WWTP with an average daily influent flow of 15,000 m^3/d, which does not comply with the effluent discharge limits prior to upgrading.

For each scenario, three treatment configurations are evaluated:

1. A baseline configuration without primary filtration
2. An upgraded configuration incorporating microsieving as the sole primary filtration step
3. A further upgraded configuration combining microsieving and sand filtration

The upgraded configurations are assessed under two levels of primary filtration performance, defined as satisfactory and excellent, corresponding to different removal efficiencies for TSS and BOD_5.

2.3.Primary filtration systems

2.3.1 Microsieve

Microsieving has emerged as a primary solids separation alternative (Gupta, 2018) (Fig. 1). Compared with conventional primary clarifiers, microsieves achieve 50-80% higher suspended solids removal with minimal footprint and reduced costs. This improvement allows efficient solids capture without expanding clarification infrastructure. During operation, filtration occurs through rotating self-cleaning cloth media. Filters typically operate with pore sizes between 200-350 µm. Retained material is collected in troughs and conveyed continuously by mechanical auger screw systems. This process produces PSS lacking cellular biomass. Such PSS exhibit solids content suitable for energy recovery. Their characteristics favor anaerobic digestion and thermal treatment applications (Gikas, 2014). Compared with conventional sludge, these solids exceed 30% dry content, simplifying handling and downstream processing. This results from absence of cellular biomass (Koliopoulos and Gikas, 2013). Accordingly, PSS may also support compost production routes.

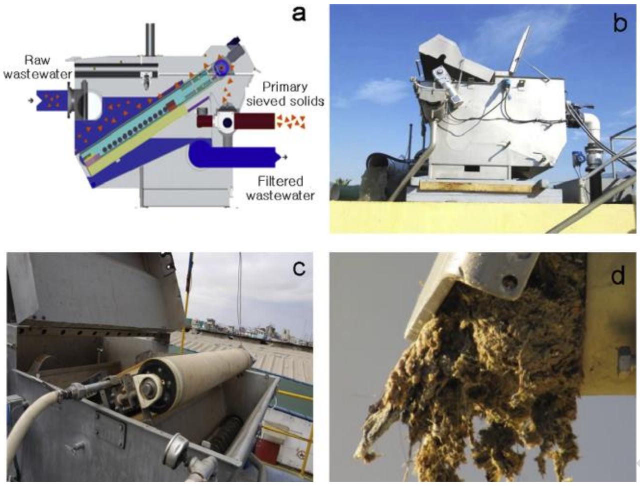

Figure 1. (a) Schematic diagram of microsieve, (b) Photograph of microsieve. (c) Fabric belt of the microsieve with cake of solids and screw auger. (d) PSS exiting the microsieve (Gikas, 2017).

2.3.2. Combined treatment: microsieving and sand filtration

In combined treatment, microsieving precedes sand filtration polishing. A representative technology is the CBUMF, a sand-based filtration system with continuous self cleaning media (Feldthusen, 2004). It operates under counter current filtration conditions driven by an airlift. Sand moves downward opposite the upward wastewater flow. Wastewater enters the filter bottom and distributes evenly through specially designed inlet arms channels. Clarified effluent is collected at the top. TSS are retained within the sand matrix during upward filtration process operation. An airlift continuously conveys sand toward the upper filter section. Accumulated organic matter is separated using a static meandric separator. Separated solids are discharged as a concentrated waste stream while regenerated sand returns downward. Sand gradually moves toward the conical base. This occurs through continuous media regeneration maintaining stable long term filtration performance during operation. When required, chemical flocculants may enhance particle removal efficiency. Their use depends on influent characteristics and operational objectives. Such additions are selected according to treatment goals and wastewater properties (Tsamoutsoglou et al., 2024).

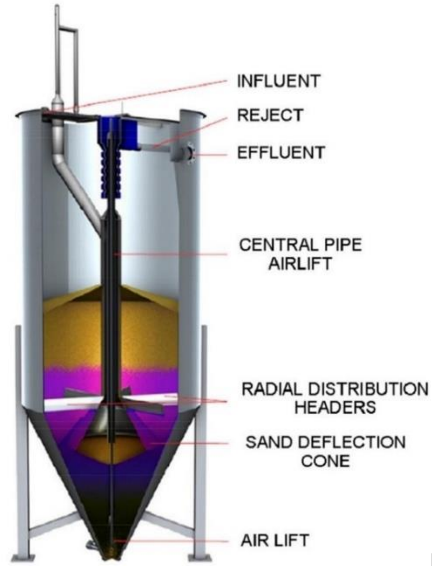

Figure 2. Schematic diagram of the CBUMF (Gikas, 2017).

Microsieving units operate with automatic self-cleaning systems and therefore do not require manual cleaning of the filter mesh (typically 200-350 μm) during normal operation. Similarly, the sand filtration unit is designed for continuous self-cleaning operation, with internal media regeneration that does not require interruption of the treatment process for backwashing, in contrast to conventional sand filters. As a result, both primary filtration systems can be operated with limited maintenance effort, while maintaining stable filtration performance. In terms of energy demand, microsieving exhibits a low specific electricity consumption of approximately 0.005 kWh/m³ of raw wastewater, while the corresponding value for continuous sand filtration is around 0.010 kWh/m³ as reported by Gikas (2017). Under the examined configurations, the only recurring operational cost may be associated with the use of coagulants, when required, to enhance filtration performance and solids removal.

2.4. Activated sludge process modeling

Fig. 3 illustrates the mass balance of the activated sludge process used in secondary wastewater treatment. Influent wastewater enters the aeration tank, where microorganisms are supplied with sufficient oxygen to promote the oxidation of organic matter. After aeration, the mixed liquor flows into the secondary clarifier, where the biomass is allowed to settle. A portion of the settled sludge is recycled back to the aeration tank as return activated sludge (RAS), while the remaining fraction is discharged to the sludge treatment line. To evaluate the potential benefits of implementing primary filtration systems in overloaded WWTPs, comprehensive mass and energy balance analyses were conducted for the activated sludge process.

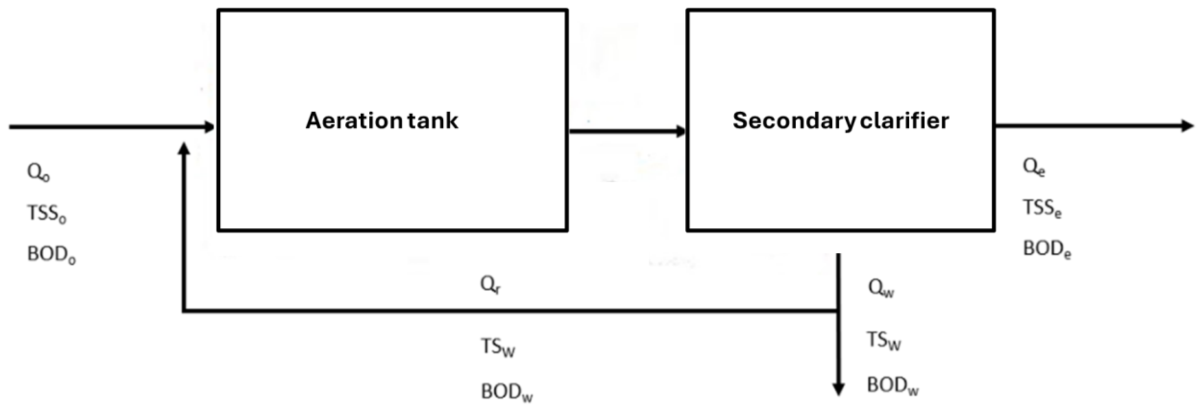

Fig 3. Mass balances in the activated sludge process.

The parameters used for the calculation of mass balances in the activated sludge process are as follows:

- Average daily influent flow rate, Q_o, m^3/d
- TSS concentration at the inlet of the aeration tank, TSS_o, mg/L
- BOD_5 concentration at the inlet of the aeration tank, BOD_o, mg/L
- Aeration tank volume, V, m^3
- Mixed liquor suspended solids (MLSS) concentration in the aeration tank, MLSS, mg/L
- Average daily effluent flow rate, Q_e, m^3/d
- Effluent TSS concentration from the secondary clarifier, TSS_e, mg/L
- Effluent BOD concentration from the secondary clarifier, BOD_e, mg/L
- Waste activated sludge flow rate, Q_w, m^3/d
- Total solids (TS) concentration in the waste activated sludge, TS_w, mg/L
- BOD_5 concentration in the waste activated sludge, BOD_w, mg/L
- Return sludge flow rate, Q_r, m^3/d
- Food-to-microorganism ratio (F/M), F:M, $kg \cdot BOD_5 / kg \cdot MLVSS \cdot d$
- HRT in the aeration tank, h
- Solids retention time (SRT) in the aeration tank, d
- Volumetric loading rate (VLR) of the aeration tank VL, $kg \cdot BOD_5 /d \cdot m^3$
- Wastewater temperature, T,℃

2.5. Design criteria and process assumptions

Table 1 presents the design ranges for VLR, food-to-microorganism ratio (F/M), and HRT adopted for extended aeration activated sludge systems. All mass and energy balance calculations were performed assuming operation within these design limits.

Table 1. Design characteristics of the activated sludge process (Tchobanoglous et al., 2003).

Activated sludge process	VL (kg $BOD_5/d \cdot m^3$)	F/M (kg BOD/kg MLVSS·d)	HRT (h)
Extended aeration	0.1-0.3	0.05-0.15	18-36

The aeration tank volume for the activated sludge process was calculated according to the Eq.1 (Tchobanoglous et al., 2003):

$$\mathbf{V} = \frac{\mathbf{BOD_o \cdot Q_o}}{\mathbf{VL}} \tag{1}$$

Where:

V is the aeration tank volume (m^3)

BOD_o is the influent BOD_5 concentration to the aeration tank (mg/L)

Q_o is the average daily influent flow rate (m^3/d)

VL is the volumetric loading rate of the aeration tank (kg BOD_5 /d·m^3)

The HRT is defined as the ratio of the aeration tank volume to the average daily influent flow rate and is calculated as follows (Eq.2) (Tchobanoglous et al., 2003):

$$\mathbf{HRT} = \frac{\mathbf{V}}{\mathbf{Q_o}} \tag{2}$$

Where:

HRT is the hydraulic retention time in the aeration tank (h)

V is the aeration tank volume (m^3)

Q_o is the average daily influent flow rate (m^3/d)

The food-to-microorganism (F/M) ratio is a fundamental operational parameter of the activated sludge process and is defined as (Tchobanoglous et al., 2003) (Eq.3):

$$\frac{\mathbf{F}}{\mathbf{M}} = \frac{\mathbf{BOD_o \cdot Q_o}}{\mathbf{MLVSS \cdot V}} \tag{3}$$

Where:

F/M is the food-to-microorganism ratio (kg BOD_5 /kg MLVSS·d)

BOD_o is the influent BOD_5 concentration (mg/L)

Q_o is the influent flow rate (m^3/d)

MLVSS is the concentration (mg/L) of volatile suspended solids in the aeration tank and is assumed to be equal to 75% of the MLSS concentration (Tchobanoglous et al., 2003).

V is the aeration tank volume (m^3)

The RAS flow rate to the aeration tank, Q_r, was calculated as follows (Tchobanoglous et al., 2003) (Eq.4):

$$\mathbf{Q_r} = \frac{\mathbf{Q_o \cdot TSS_o}}{\mathbf{TS_w - MLSS}} \tag{4}$$

Where:

Q_r is the return activated sludge flow rate (m^3/d)

Q_o is the influent flow rate (m^3/d)
TSS_o is the influent TSS concentration (mg/L)
TS_w is the total solids concentration in waste activated sludge (mg/L)
MLSS is the mixed liquor suspended solids concentration in the aeration tank (mg/L)

The waste activated sludge flow rate, Q_w, was calculated using the following Eq.5 (Tchobanoglous et al., 2003):

$$\mathbf{Q_w} = \frac{\frac{\mathbf{V \cdot X}}{\mathbf{SRT}} - \mathbf{Q_e \cdot TSS_e}}{\mathbf{TS_w}} \qquad \mathbf{5}$$

Where:
Q_w is the waste activated sludge flow rate (m^3/d)
V is the aeration tank volume (m^3)
X is the MLSS concentration in the aeration tank (mg/L)
SRT is the solids retention time (d)
Q_e is the effluent flow rate (m^3/d)
TSS_e is the effluent TSS concentration (mg/L)
TS_w is the total solids concentration in the waste sludge (mg/L)

Oxygen serves as the terminal electron acceptor in the energy metabolism of aerobic heterotrophic microorganisms in the aeration tank. The oxygen demand associated with carbonaceous BOD_5 removal and nitrification was calculated using the following Eq.6 (Tchobanoglous et al., 2003):

$$\mathbf{Oxygen\ demand} = \mathbf{Q_o} \cdot \left\{ (\mathbf{BOD_o} - \mathbf{BOD_e}) \cdot \left[\left(\frac{\mathbf{1}}{\mathbf{f}} \right) - (\mathbf{1.42} \cdot \mathbf{Y_{obs}}) \right] + \mathbf{4,57} \cdot (\mathbf{TKN_o} - \mathbf{NH_4} - \mathbf{N}) \right\} \qquad \mathbf{6}$$

Where:
Oxygen demand is the total oxygen requirement for carbonaceous BOD_5 removal and nitrification (kg O_2/h)
Q_o is the average daily influent flow rate (m^3/d)
BOD_o is the influent BOD_5 concentration (mg/L)
BOD_e is the effluent BOD_5 concentration (mg/L)
f is the is the BOD_5/BOD_u, ratio , assumed equal to 0.68 (Tchobanoglous et al., 2003)
Y_{obs} is the observed biomass yield coefficient (kg VSS/kg BOD_5)
TKN_o is the influent total Kjeldahl nitrogen concentration (mg/L)
NH_4-N is the effluent ammonium nitrogen concentration (mg/L)

The observed yield coefficient, Y_{obs}, was calculated as follows (Tchobanoglous et al., 2003) (Eq.7):

$$\mathbf{Y_{obs}} = \frac{\mathbf{Y}}{(\mathbf{1} + \mathbf{k_{nd}} \cdot \mathbf{SRT})} \qquad \mathbf{7}$$

Where:

Y_{obs} is the observed yield coefficient with recycle (kg VSS / kg BOD_5)

Y is the synthesis yield coefficient, equal to 0,6, kg VSS/kg BOD_5 (Tchobanoglous et al., 2003)

k_{nd} is the endogenous decay coefficient (1/d)

SRT is the solids retention time (d)

The endogenous decay coefficient, k_{nd}, for a wastewater temperature of 15 °C was calculated using the following temperature correction (Eq.8) (Tchobanoglous et al., 2003):

$$\mathbf{K_{nd} = k_{d20} \cdot 1,024^{(T-20)}} \quad \mathbf{8}$$

Where:

K_{nd} is the endogenous decay coefficient at temperature T (1/d)

k_{d20} is the endogenous decay coefficient at 20 °C, equal to 0,06 1/d (Lin, 2007)

T is the wastewater temperature (°C)

The power requirement, P_W, to meet the oxygen demand in the aeration tank was calculated as follows (Tchobanoglous et al., 2003) (Eq.9):

$$\mathbf{P_W = \frac{Oxygen\ demand}{SAE}} \quad \mathbf{9}$$

Where:

P_W is the power requirement for aeration (kWh/h)

Oxygen demand is the total oxygen requirement (kg O_2/h)

SAE is the standard aeration efficiency (SAE), defined as the oxygen transfer rate per unit of energy input. For diffused aeration systems, SAE values typically range from 2 to 8 kg O_2/kWh according to the literature (Tchobanoglous et al., 2003). A value of 5 kg O_2/kWh was selected for the calculations of both scenarios.

Because the same aeration system characteristics and SAE value were assumed for all evaluated scenarios, the resulting specific aeration energy consumption (kWh/m³) remains comparable between scenarios, while absolute aeration energy demand varies according to the calculated oxygen requirements.

The energy requirement of the sludge treatment line, including thickening, dewatering and composting, is estimated using the concept of specific energy consumption (SEC), which relates the total energy consumption to the secondary sludge flow rate. The total energy consumption of the sludge line, E_{sludge}, is calculated as follows (Eq. 10):

$$\mathbf{E_{sludge} = Q_W \cdot SEC_{sludge}} \quad \mathbf{10}$$

Where:

E_{sludge} is the total energy consumption of the sludge treatment line (kWh/d),

Q_W is the secondary sludge (waste activated sludge) flow rate (m^3/d), and

SEC_{sludge} is the specific energy consumption of the sludge treatment line (kWh/m^3). A constant SEC value of 1.0 kWh/m^3 of secondary sludge was adopted for the calculations for both scenarios (Tchobanoglous et al., 2003).

2.6 Influent and effluent characteristics and primary filtration performance

The influent and effluent wastewater quality characteristics adopted for the mass and energy balance calculations were selected in full consistency with the methodological framework described in Sections 2.1-2.5. Average influent wastewater quality data from a representative municipal WWTP operating under Mediterranean conditions were used as a reference case, reflecting the high hydraulic and organic loading conditions typically encountered in overloaded WWTPs in Southern Europe. For all evaluated configurations, the same average influent flow rate and raw wastewater characteristics were applied in order to isolate the effects of primary filtration on the performance of the downstream activated sludge process. Any reductions in TSS and BOD_5 entering the aeration tanks were attributed exclusively to the assumed removal efficiencies of the primary filtration systems, namely microsieving and combined microsieving-sand filtration. The selected removal efficiencies correspond to conservative and upper-range values reported for full-scale applications in the literature. For each treatment scenario, two levels of primary filtration performance were considered, defined as satisfactory and excellent. These performance levels directly determine the influent TSS and BOD_5 concentrations at the inlet of the biological treatment stage and, consequently, influence the calculated aeration tank volumes, oxygen demand, aeration energy consumption, and secondary sludge production.

Scenario 1 represents an overloaded WWTP receiving 10,000 m^3/d influent. Under baseline operating conditions, the WWTP complies with effluent discharge limits set by Directive (EU) 2024/3019. Influent and effluent characteristics and assumed primary filtration performance are summarized in Table 2. Microsieving reduces influent TSS and BOD_5 by 30% and 15%. Under excellent performance, TSS and BOD_5 are reduced by 60% and 35%, respectively. Despite this substantial reduction in organic and solids loading entering biological treatment, effluent TSS and BOD_5 concentrations were assumed constant across all configurations. This assumption reflects stable secondary treatment performance under extended aeration conditions and enables direct comparison of process requirements and energy demand.

Scenario 2 corresponds to a more severely overloaded WWTP with an average daily influent flow rate of 15,000 m^3/d, which fails to comply with the effluent quality requirements of Directive (EU) 2024/3019 under baseline operating conditions. The influent and effluent quality characteristics and the assumed primary filtration performance for this scenario are presented in Table 2. The introduction of primary filtration substantially reduces the organic and solids loading entering the biological treatment stage. Under both satisfactory and excellent performance levels of the primary filtration systems, effluent TSS and BOD_5 concentrations were assumed to comply with the regulatory discharge limits. This highlights the effectiveness of primary filtration as an upgrading strategy capable of restoring compliance in overloaded WWTPs without the need for biological reactor expansion.

Table 2. Influent and effluent quality characteristics and assumed performance of primary filtration systems for Scenario 1 and 2.

Scenario 1			
Parameter	Overloaded WWTP	Unit upgrade with microsieving	Unit upgrade with combined treatment
Influent parameters	-	Satisfactory performance	Excellent performance
Average daily flow rate, (m^3/d)	10,000	10,000	10,000
TSS removal, (%)	-	30	60
BOD_5 removal, (%)	-	15	35
Influent TSS, TSS_0 (mg/L)	713	499	285
Influent BOD_5, BOD_0 (mg/L	466	396	303
Effluent TSS, TSS_e (mg/L)	30	30	30
Effluent BOD_5, BOD_e (mg/L)	20	20	20
Effluent TSS limit (Directive (EU) 2024/3019)	< 35 mg/L	< 35 mg/L	< 35 mg/L
Effluent BOD_5 limit (Directive (EU) 2024/3019)	< 25 mg/L O_2	< 25 mg/L O_2	< 25 mg/L O_2
Scenario 2			
Parameter	Overloaded WWTP	Unit upgrade with microsieving	Unit upgrade with combined treatment
Influent parameters	-	Satisfactory performance	Excellent performance
Average daily flow rate, (m^3/d)	15,000	15,000	15,000
Influent TSS, TSS_0 (mg/L)	713	499	285
Influent BOD_5, BOD_0 (mg/L)	466	396	303
Effluent TSS, TSS_e (mg/L)	70	30	30
Effluent BOD_5, BOD_e (mg/L)	50	20	20
Effluent TSS limit (Directive (EU) 2024/3019)	< 35 mg/L	< 35 mg/L	< 35 mg/L
Effluent BOD_5 limit (Directive (EU) 2024/3019)	< 25 mg/L O_2	< 25 mg/L O_2	< 25 mg/L O_2

Table 3 summarizes all parameters and values used in the steady-state mass and energy balance calculations for the activated sludge process. The same set of assumptions was applied to both evaluated scenarios, allowing direct comparison between baseline and upgraded configurations. Differences between scenarios are solely related to influent flow rate and resulting process loading.

Table 3. Parameters and values used for steady-state mass and energy balance calculations.

Parameter	Scenario	Overloaded WWTP	Microsieving upgrade - satisfactory	Microsieving upgrade - maximum	Combined treatment - satisfactory	Combined treatment - maximum
Average daily flow (Q_o), m³/d	Scenario 1	10,000	10,000	10,000	10,000	10,000
	Scenario 2	15,000	15,000	15,000	15,000	15,000
TSS removal (%)	Both	-	30	60	60	90
BOD_5 removal (%)	Both	-	15	35	35	55
Influent TSS in aeration tank (TSS_o), mg/L	Both	713	499	285	285	71
Influent BOD_5 in aeration tank (BOD_o), mg/L	Both	466	396	303	303	210
Influent TKN_o, mg/L	Both	8	8	8	8	8
Effluent in secondary clarifier						
Effluent TSS (TSS_e), mg/L	Scenario 1	30	30	30	30	30
	Scenario 2	70	30	30	30	30
Effluent BOD_5 (BOD_e), mg/L	Scenario 1	20	20	20	20	20
	Scenario 2	50	20	20	20	20
Effluent NH_4-N, mg/L	Scenario 1	1.5	1.5	1.5	1.5	1.5
	Scenario 2	3.0	1.5	1.5	1.5	1.5
Activated sludge designparameters						
MLSS, mg/L	Both	3,500	3,500	3,500	3,500	3,500
MLVSS/MLSS ratio, -	Both	0.75	0.75	0.75	0.75	0.75
MLVSS, mg/L	Both	2,625	2,625	2,625	2,625	2,625
VL, kg BOD_5/d·m³	Both	0.30	0.30	0.30	0.30	0.30
F/M ratio, kg BOD_5/kg MLVSS·d	Both	0.11	0.11	0.11	0.11	0.11
HRT, h	Both	37	32	24	24	17
SRT, d	Both	30	30	30	30	30
Wastewater temperature, °C	Both	15	15	15	15	15
Kinetic and stoichiometric parameters						
f = BOD_5/BODu, -	Both	0.68	0.68	0.68	0.68	0.68
Y, kg VSS/kg BOD_5	Both	0.60	0.60	0.60	0.60	0.60
K_{nd} at 20 °C, 1/d	Both	0.060	0.060	0.060	0.060	0.060
K_{nd} at 15 °C, 1/d	Both	0.053	0.053	0.053	0.053	0.053
Y_{obs}, kg VSS/kg BOD_5	Both	0.30	0.30	0.30	0.30	0.30
Energy parameters						
SAE, kg O_2/kWh	Both	5	5	5	5	5
SEC, kWh/m³	Both	1.0	1.0	1.0	1.0	1.0

2.7 Sensitivity analysis

To evaluate the robustness of the obtained results, a sensitivity analysis was conducted on key operational and design parameters influencing aeration demand and reactor sizing. Influent TSS and BOD_5 removal efficiencies of the primary filtration systems were varied by ±20%, while SAE and SRT were independently varied within typical operational ranges reported in the literature. The objective of this analysis was to assess the stability of the predicted energy savings and aeration tank volume reductions under realistic operational uncertainty.

3. Results

3.1 Scenario 1: moderately overloaded WWTP (10,000 m^3/d)

Implementing primary filtration upstream reduces hydraulic and organic loading of overloaded WWTPs. These upstream load reductions directly lowered aeration requirements, energy consumption, and secondary sludge production. Table 4 presents calculated performance indicators for Scenario 1. Baseline operation and post upgrade configurations are compared. Microsieving and combined microsieving sand filtration were evaluated under satisfactory and excellent performance levels.

Table 4. Summary of calculated performance indicators for scenario 1.

Parameter	Baseline	Microsieving	Microsieving	Combined treatment (microsieve followed by CBUMF)	Combined treatment (microsieve followed by CBUMF)
Performance		Satisfactory	Excellent	Satisfactory	Excellent
Aeration tank volume, (m^3)	15,533	13,200	10,100	10,100	7,000
Reduction (%)	-	15	35	35	55
Oxygen demand, (kg O_2/h)	235	202	157	157	113
Reduction (%)	-	14	33	33	52
Aeration energy, (kWh/m^3)	0.11	0.10	0.08	0.08	0.05
Reduction (%)	-	9	27	27	54
Secondary sludge, (m^3/d)	189	155	110	110	65
Reduction (%)	-	19	43	43	66
Sludge energy requirements, (kWh/d)	189	155	110	110	65
Reduction, (%)	-	19	43	43	66

The results indicated that microsieving alone provided significant performance improvements, yielding reductions of up to 33% in oxygen demand and 27% in aeration energy consumption under excellent operating conditions. However, the combined microsieving-sand filtration configuration consistently achieved the greatest reductions across all evaluated indicators. Under excellent combined treatment performance, aeration energy consumption was reduced by more than 50%, while aeration tank volume and secondary sludge production decreased by approximately 55% and 66%, respectively. The energy requirements of the sludge treatment line were reduced by 19% and up to 43% with microsieving, while the combined treatment configuration achieved a reduction of approximately 66% under excellent operating conditions. These findings demonstrated the strong sensitivity of extended aeration activated sludge systems to upstream removal of suspended solids and biodegradable organic matter.

3.2 Primary and secondary sludge production (Scenario 1)

The reduction in secondary sludge production achieved through the implementation of primary filtration systems is accompanied by the generation of PSS characterized by a high dry solids content (Gikas, 2014). This redistribution of solids from the biological treatment stage to the primary treatment stage significantly alters the overall sludge production profile. Table 5 summarizes the resulting distribution of sludge streams for Scenario 1 under baseline conditions and after upgrading with microsieving and combined microsieving-sand filtration.

Table 5. Primary and secondary sludge production for scenario 1.

Parameter	**Baseline**	**Microsieving**	**Microsieving**	**Combined treatment (microsieve followed by CBUMF)**	**Combined treatment (microsieve followed by CBUMF)**
		Satisfactory	Excellent	Satisfactory	Excellent
Secondary sludge, (t/d, wet)	197	161	114	114	68
Reduction, (%)	-	19	43	43	66
PSS, (t/d, dry)	-	0.5	0.6	0.6	0.6

Primary filtration substantially reduced secondary biological sludge production. Reductions ranged from 19% under satisfactory microsieving to 66% under excellent combined treatment. In contrast, PSS production remained relatively constant. This stream formed a small yet highly concentrated solids fraction. Unlike secondary sludge, PSS exhibited higher dry solids content, lower water binding, improved dewaterability, and reduced handling volumes. Overall sludge treatment line loading decreased despite additional solids. Redistributing solids improved operational flexibility and supported downstream energy recovery through anaerobic digestion or thermal treatment.

3.3 Scenario 2: severely overloaded WWTP (15,000 m³/d)

Under baseline conditions, Scenario 2 failed effluent quality compliance. This failure reflects severe hydraulic and organic overloading of the biological treatment stage. Primary filtration implementation upstream restored regulatory compliance. It also substantially reduced biological treatment requirements. Table 6 summarizes calculated performance indicators for Scenario 2 under baseline operation and after upgrading with microsieving and combined microsieving sand filtration, assuming satisfactory and excellent performance levels.

Table 6. Summary of calculated performance indicators for scenario 2.

Parameter	Baseline	Microsieving	Microsieving	Combined treatment (microsieve followed by CBUMF)	Combined treatment (microsieve followed by CBUMF)
		Satisfactory	Excellent	Satisfactory	Excellent
Aeration tank volume, (m^3)	23,300	19,800	15,150	15,150	10,500
Reduction, (%)	-	15	35	35	54
Oxygen demand, (kg O_2/h)	348	303	236	236	170
Reduction, (%)	-	13	32	32	51
Aeration energy, (kWh/m^3)	0.11	0.10	0.08	0.08	0.05
Reduction, (%)	-	9	27	27	54
Secondary sludge, (m^3/d)	209	165	165	165	97
Reduction, (%)	-	21	21	21	54

Microsieving alone substantially reduced hydraulic and organic loading on the biological treatment stage. Under excellent operating conditions, oxygen demand decreased by up to 32% and aeration energy consumption by 27%. The combined microsieving and sand filtration configuration consistently delivered the greatest overall performance benefits. When operating at excellent combined treatment performance, aeration energy demand was reduced by more than 50%, while aeration tank volume and secondary sludge production decreased by approximately 54%. Importantly, compliance with effluent TSS and BOD_5 limits was achieved in all upgraded configurations without biological reactor expansion, demonstrating that primary filtration could serve as a space-efficient and energy-efficient capacity-recovery and compliance-restoration strategy for severely overloaded WWTPs.

Table 7 summarizes the results of the sensitivity analysis of key operational and design parameters affecting aeration energy demand and aeration tank volume, highlighting the relative influence of primary filtration performance, aeration efficiency, and biological operating conditions on the robustness of the predicted energy and volume reductions.

Table 7. Sensitivity analysis of key operational and design parameters affecting aeration energy demand and aeration tank volume

Parameter varied	Variation range	Effect on aeration energy demand	Effect on aeration tank volume	Sensitivity level	Key interpretation
Influent TSS removal efficiency (primary filtration)	±20%	±15-25% change in aeration energy savings	±10-20% change in required aeration volume	High	Upstream particulate removal is the primary determinant of oxygen demand and reactor sizing; small deviations in removal efficiency result in disproportionate energy impacts.
Influent BOD_5 removal efficiency (primary filtration)	±20%	±10-20% change in aeration energy demand	±10-15% change in aeration volume	High	Demonstrates nonlinear aeration response to variations in biodegradable organic load reduction.
Standard aeration efficiency (SAE)	2-8 kg O_2/kWh	Affects absolute energy consumption while maintaining relative energy savings (>40%)	No significant effect	Moderate	Energy benefits from primary filtration remain consistent under conservative aeration efficiency assumptions.
Solids retention time (SRT)	Extended aeration range	±5-10% change in aeration energy demand	±10-15% change in reactor volume	Low-Moderate	Biological operating parameters influence sizing but are secondary to influent load reduction.
Combined variation of all parameters	Realistic operational uncertainty	Net energy savings remain >30-40%	Volume reductions remain >35-45%	Low risk	Results indicate robustness of conclusions under realistic WWTP operational variability.

The sensitivity analysis confirms robustness of the main findings. Variations in primary filtration removal efficiencies exerted the strongest influence on aeration energy demand and aeration tank volume requirements. A ±20% change caused substantial variability. Aeration energy savings varied by approximately ±15-25%. Required aeration tank volume changed by approximately ±10-20%. Despite this variability, combined microsieving and sand filtration consistently achieved energy reductions exceeding 40%. This suggests that the predicted benefits remain relatively stable under operational uncertainty. Changes in standard aeration efficiency affected absolute energy consumption significantly. Relative aeration energy savings remained within ±3%. Variations in SRT produced comparatively smaller effects. Aeration energy demand varied by 5-10%. Aeration tank volume changed by approximately 10-15%. When all parameters varied simultaneously within realistic bounds, combined treatment maintained savings above 30-40%. Aeration tank volume reductions exceeded 35-45%. These results indicate that the conclusions are not highly sensitive to individual parameter assumptions. Primary filtration remains the dominant driver of energy and capacity benefits.

4. Discussion

Results from both scenarios indicate substantial reductions in aeration requirements following implementation of primary filtration. In Scenario 1, microsieving reduced oxygen demand by 14-33%, while combined microsieving-sand filtration achieved reductions up to 52%. Similar trends were observed in Scenario 2 under higher flow conditions. There, microsieving lowered oxygen demand by 13-32%, while combined treatment achieved reductions up to 51%. These reductions exceeded corresponding influent BOD_5 decreases of 15-35%. This nonlinear response reflects lower carbon oxidation requirements and reduced endogenous respiration rates in the biological treatment. Limiting particulate and slowly biodegradable organic matter lowers immediate oxygen consumption. It also reduces long-term maintenance energy demand. The modeled aeration reductions are consistent with observations reported for full-scale activated sludge plants. At the Las Calaveras WWTP, USA, aeration power decreased from approximately 48.5 to 42.5 kW per 3,785 m^3/d, representing a 12% reduction. Comparable decreases were reported at the Manteca WWTP, USA, from 57.4 to 46.2 kW per 3,785 m^3/d (20%), and at the Lancaster WWTP, from 50.7 to 41.0 kW per 3,785 m^3/d (19%) (Caliskaner and Pena-Tijerina, 2019). This agreement suggests that aeration energy demand is sensitive to upstream removal of particulate biodegradable organic matter. Modest improvements in primary treatment can yield disproportionate energy savings, particularly in overloaded extended aeration activated sludge systems.

A direct comparison showed a clear hierarchy in upgrading performance. Microsieving alone offered model-estimated benefits, with aeration energy reductions ranging from 9 to 27% across the evaluated scenarios. The addition of sand filtration further improved performance, particularly under excellent operating conditions. In both scenarios, the combined configuration resulted in additional energy savings. These gains were attributed to the improved removal of fine suspended particulate organics that otherwise bypassed microsieves and entered biological treatment. Within aeration tanks, such fine particles degraded slowly and contributed disproportionately to oxygen demand and endogenous respiration during extended aeration operation (Metcalf and Eddy, 1991). Consequently, upstream removal reduced both short- and long-term aeration requirements. Full-scale observations reported in the literature provide qualitative context for these findings. At the LCWD, Manteca, and Lancaster WWTPs, USA, fine solids bypassing primary treatment were identified as a key driver of aeration energy demand (Caliskaner and Pena-Tijerina, 2019). Effective upstream removal helped protect biological reactors and stabilize process performance, thereby maximizing aeration energy savings under high organic loading and overloaded operating conditions.

Reductions in influent loading reduce required aeration tank volumes. In Scenario 1, aeration tank volumes decreased by 15-35% with microsieving and up to 55% under combined microsieving and sand filtration. Similar reductions were observed in Scenario 2, with maximum volume savings reaching approximately 54%. These reductions are particularly important for overloaded WWTPs. Conventional upgrading strategies typically rely on costly biological reactor expansion. The results demonstrate that primary filtration can effectively substitute reactor enlargement. This enables substantial treatment capacity recovery within the existing plant footprint. Modeled volume reductions are qualitatively consistent with reported full-scale APF observations. At the Las Calaveras WWTP, activated sludge volume decreased from approximately 2,950 to 2,765 m^3 per 3,785 m^3/d corresponding to a 6% reduction. At the Manteca WWTP, required volume decreased from 2,270 to 1,590 m^3 per 3,785 m^3/d, representing a 30% reduction. At the Lancaster WWTP, activated sludge volume decreased from 1,480 to 1,140 m^3 per 3,785 m³/d, equivalent to a 22% reduction (Caliskaner and Pena-Tijerina, 2019). Based on the modelling results and plant-scale observations, primary filtration represents a feasible alternative to biological reactor expansion. This is of particular importance for overloaded WWTPs where space is limited.

Implementation of primary filtration reduced secondary sludge production substantially. Reductions ranged from 19-66% in Scenario 1 and from 21-54% in Scenario 2. These decreases are directly linked to reduced biomass growth within activated sludge systems. By limiting biodegradable particulate matter entering the biological stage, primary filtration significantly reduces excess biomass generation and endogenous decay requirements. At the same time, particulate organic matter is diverted upstream as PSS. This diversion partially offsets reductions in secondary sludge production. However, PSS differ fundamentally from biological sludge in physical characteristics. They exhibit higher dry solids content and lower water binding capacity. This improves dewaterability and reduces volumetric handling requirements substantially. Consequently, overall sludge treatment line loading decreases despite an additional solids stream. These trends are consistent with observations reported at the Lancaster and Manteca WWTPs (Caliskaner and Pena-Tijerina, 2019). There, reduced biological reactor volume and aeration demand coincided with lower secondary sludge production. Concurrent diversion of particulates reduced hydraulic and solids loading downstream. This redistribution improves sludge handling performance and enhances operational robustness, especially under high loading and overloaded operating conditions.

Shifting from secondary sludge to PSS has a positive effect on energy recovery potential in WWTPs. Due to its lower cellular biomass content and higher heating value, PSS is more suitable for anaerobic digestion and thermal treatment. In Scenario 1, PSS production was estimated at 0.5-0.6 t/d, indicating the availability of an internal energy source that is relevant for plant operation. Primary filtration also reduced aeration demand. In the configurations examined, aeration energy savings of up to 54% were observed. Under these conditions, a 54% decrease in aeration demand corresponds to an overall electricity reduction of approximately 25-30%. For a WWTP serving 10,000 PE, with a typical electricity demand of 300-400 kWh/PE·y, the resulting annual energy savings are estimated at 0.8-1.2 GWh. At electricity prices of 0.15-0.20 €/kWh, this corresponds to annual operational savings in the range of 120,000-240,000 €. These values underline the relevance of primary filtration from an energy management perspective. In addition, diverting organic matter to the sludge line increased biogas production. At the Lancaster WWTP, biogas production increased from 320 to 430 m³/d for a treated flow of 3,785 m³/d. Comparable increases were observed at the Manteca WWTP. In both cases, increased biogas production occurred alongside reduced aeration demand, indicating that energy savings and energy recovery can be achieved simultaneously.

In Scenario 2, the baseline configuration did not meet effluent quality requirements. After the introduction of primary filtration, compliance was achieved in all upgraded configurations, without any increase in biological reactor volume. The results show that primary filtration can be applied as an upgrading measure under the examined conditions. In this case, compliance was mainly achieved by reducing the influent load rather than by increasing the intensity of biological treatment. Consequently, overall process demands were reduced, and plant operation became less susceptible to unstable conditions. This is of particular relevance for small and medium-sized WWTPs, where available space for expansion is limited. Primary filtration may also affect biological nutrient removal. By removing part of the influent organic carbon upstream of the aeration tank, the availability of readily biodegradable carbon for heterotrophic denitrification may decrease, potentially influencing nitrogen removal. However, studies indicate that primary filtration does not necessarily compromise the carbon-to-nitrogen (C:N) ratio required for effective nutrient removal when sufficient biodegradable carbon remains (Bahreini et al., 2021; Lema and Martínez, 2017). At the Lancaster WWTP, NOx-N concentrations in the secondary effluent increased from 6.8 to 14.5 mg/L following the implementation of primary biofiltration. At the Manteca WWTP, NOx-N concentrations increased from 4.1 to 6.1 mg/L. At Lancaster, a further increase from 3.9 to 7.3 mg/L was also observed. These changes were addressed through operational measures rather than additional infrastructure. At the Lancaster WWTP, adjustment of dissolved oxygen setpoints reduced effluent NOx-N concentrations to 9.3 mg/L. As a result, the net increase in NOx-N was limited to approximately 17%. Overall, the results indicate that regulatory compliance can be maintained through a combination of load reduction and targeted operational control of biological processes.

The results show that primary filtration can be beneficial for WWTPs operating under overload conditions. The assessment was carried out using steady-state mass and energy balances. These balances were applied in the same way for all cases examined in this study. Dynamic behaviour of the systems was not analysed. Effects related to daily flow variations, seasonal changes, or short-term loading events were therefore not included. Despite these limitations, similar trends were observed in both scenarios. This suggests that the effects identified are not case-specific and are likely relevant for typical operating conditions in municipal WWTPs. While the findings indicate that primary filtration can substantially improve effluent quality and reduce biological treatment requirements, verification under real operating conditions is required. In particular, the implications for regulatory compliance need to be confirmed through full-scale implementation and operational data. The application of combined microsieving and sand filtration systems should also be evaluated using life-cycle approaches. A detailed life-cycle cost analysis was not included in the present work. The present analysis focused primarily on the water treatment line, particularly on aeration demand and biological reactor sizing. The effects of primary filtration on the sludge treatment line and on the overall plant energy balance were addressed using simplified assumptions. A more comprehensive evaluation including detailed sludge treatment modelling and full plant energy balance assessment would further clarify the role of primary filtration within the broader regulatory framework. Significant reductions in energy demand were associated with lower aeration requirements. Aeration generally represents about 30-60% of total electricity consumption in WWTPs. Reductions of up to 54% in aeration demand therefore have a noticeable effect on overall energy use. In addition, primary filtration systems require limited space and may reduce capital costs. The need for expansion of biological reactors can be avoided, which is particularly important for urban WWTPs with restricted available area. Taken together, the results indicate that primary filtration can provide practical advantages for plant upgrading. Both short-term operational improvements and longer-term infrastructure benefits can be achieved. While advanced primary treatment can lead to a reduction in overall organic loading, several studies have demonstrated that primary filtration does not significantly compromise the availability of easily biodegradable carbon fractions. As a result, no negative impact on the carbon-to-nitrogen (C:N) or carbon-to-phosphorus (C:P) ratios necessary for efficient biological nitrogen and phosphorus removal has been reported (Bahreini et al., 2021; Lema and Martinez, 2017). In addition to its influence on biological processes and nutrient removal efficiency, the implementation of primary filtration also affects sludge handling strategies, thereby having notable consequences for the overall energy balance of the treatment facility.

5. Conclusions

Many municipal WWTPs operate under continuous hydraulic and organic overloading. In such cases, upgrading through the expansion of biological reactors is often not feasible due to space limitations, increasing energy costs, and stricter effluent quality requirements. Primary filtration may be applied as an alternative upgrading approach for overloaded WWTPs. In this study, microsieving and combined microsieving-sand filtration were examined as upstream load reduction options for overloaded municipal WWTPs operated under extended aeration conditions. The analysis focused on steady-state operation of WWTPs subjected to hydraulic and organic stress. Both configurations were shown to reduce the particulate and biodegradable organic loads entering the biological stage. As a consequence, oxygen demand, aeration energy consumption, and required aeration tank volumes were substantially reduced in both evaluated scenarios. Aeration energy demand was reduced by up to 54%, while the required aeration volume was reduced by up to 55%. These reductions exceeded the corresponding decreases in influent BOD_5, indicating that upstream removal of particulate organic matter can have a non-linear effect on aeration requirements. Primary filtration also reduced the production of secondary biological sludge by limiting biomass growth in the activated sludge system. Organic solids were instead removed upstream as PSS with higher dry solids content, which is more suitable for sludge handling and anaerobic digestion. The combined microsieving-sand filtration configuration consistently outperformed microsieving alone, as it enabled the removal of fine particulate fractions that would otherwise remain in the biological reactors and degrade slowly under extended aeration conditions. In the scenario representing severe overloading, the modelling results indicate that effluent quality compliance could be achieved without expansion of the biological reactors, provided that the assumed filtration performance is attained. Overall, the findings of this study suggest that primary filtration has the potential to serve as a space-efficient upgrading strategy for overloaded municipal WWTPs, within the limitations of the applied steady-state modelling framework. Further research based on dynamic modelling and full-scale operational data is required to validate the predicted energy savings and compliance outcomes under real WWTP operating conditions.

6. Abbreviations

Abbreviation	Definition
APF	Advanced Primary Filtration
BOD_5	Biochemical Oxygen Demand (over five days)
CBUMF	Continuous Backwash Upflow Media Filter
COD	Chemical Oxygen Demand
F/M	Food-to-Microorganism Ratio
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MNPLs	Micro- and nanoplastics
PE	Population Equivalent
PSS	Primary Sieved Solids
RAS	Return Activated Sludge
SAE	Standard Aeration Efficiency
SRT	Solids Retention Time
TSS	Total Suspended Solids
VLR	Volumetric Loading Rate
WWTP	Wastewater Treatment Plant

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