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Sustainable water treatment solutions: Enhancing efficiency with tube settlers to address water scarcity

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Abstract:

Water scarcity has emerged as a pressing global challenge, exacerbated by factors such as climate change, population growth, and industrialization (Nations, 2023). One such promising technology is the integration of tube settlers into existing water treatment frameworks. Tube settlers are gravity-assisted sedimentation devices that enhance the efficiency of the clarification process by promoting the aggregation and settling of suspended solids (AWWA, 2011). The application of tube settler technology has significantly advanced water treatment by reducing detention time and enhancing sedimentation through high-rate sedimentation principles. This study evaluates the impact of integrating innovative tube settlers into the sedimentation processes of water treatment plants. A comparative analysis was conducted to compare conventional accelerator clarifiers with enhanced clarifiers equipped with tube settlers. Tube settler groups, inclined at a 60° angle and measuring 90 cm in lengthir, were used to facilitate the flow of screened raw water. Key parameters including the number of backwashes per day, energy consumption, and removal efficiencies of Al^{3+}, Fe^{3+}, turbidity, total suspended solids (TSS), and biological agents (diatoms, nematodes, rotifers, protozoa, and algae) were assessed. The study highlighted significant reductions in treatment costs, with a 25% decrease in electricity consumption and improved contaminant removal. Clarifiers equipped with tube settlers demonstrated significantly higher removal efficiencies for all parameters measured, with average removal rates of 74% for Al^{3+}, 60% for Fe^{3+}, 77% for total suspended solids (TSS), and 92% for algae. These findings confirm that integrating tube settlers greatly enhances the efficiency of water treatment processes. It is recommended that designers of water treatment plants include tube settlers in the initial design phase, and prioritize re-engineering efforts to ensure optimal operation.

Keywords: Water treatment technologies; Sedimentation; Water treatment efficiency; Water clarification; Water pollution

1. Introduction

Water scarcity is an increasing global challenge caused by factors such as population growth, urbanization, climate change, and the excessive use of freshwater resources. The United Nations has reported that nearly half of the world's population could experience water stress by 2030 unless more sustainable water management practices are implemented (UNESCO, 2023). This intensifying crisis necessitates innovative and cost-effective approaches to water treatment and conservation, particularly in regions with limited access to potable water (Dos Santos et al., 2023). Conventional water treatment technologies often require significant infrastructure, energy, and operational costs, which can limit their application in resource-constrained settings. Specifically, traditional sedimentation methods are facing criticism due to their high energy consumption, large space requirements, and limited effectiveness in removing fine particles and biological contaminants (Bianchini et al., 2019). In contrast, low-cost and energy-efficient technologies such as tube settlers offer a promising alternative. Tube settlers, also known as lamella clarifiers, enhance sedimentation processes by increasing the effective settling area, thereby accelerating the removal of suspended solids and reducing the footprint of clarifiers (Bhorkar et al., 2017; Gurjar et al., 2017). The primary mechanism of tube settlers involves Boosting sediment absorption by reducing the upward velocity of particles (Al-Dulaimi and Racoviţeanu, 2019). Their modular design, ease of retrofitting into existing systems, and minimal maintenance requirements make them particularly suitable for decentralized or small-scale water treatment facilities. The integration of tube settlers into existing treatment frameworks not only improves water clarity and quality but also contributes to the sustainability of treatment operations by lowering chemical consumption and sludge production. These improvements align with the principles of circular economy and environmental stewardship, emphasizing the reuse of treated water and reduction of environmental impact (Mobasher Moghadam and Fataei, 2017). These advancements are essential to meet the needs of large urban populations and to promote sustainable water resource management (Sunny, 2024). These systems demand extensive infrastructure and often struggle to capture fine particles (e.g., sub-10 μm) and biological contaminants, such as protozoa and algae (Shammas and Wang, 2015). Several studies have shown that integrating tube settlers into sedimentation systems enhances the physical and chemical quality of treated water while reducing energy use (Shammas and Wang, 2015). Recent research has demonstrated that tube settlers can enhance flow dynamics, mitigating issues such as short-circuiting and dead zones commonly found in traditional sedimentation tanks. Additionally, tube settlers have proven effective in improving water quality parameters (Gurjar et al., 2017). For instance, Afiatun et al. (2021) reported up to 93.5% turbidity removal when combining tube settlers with electrocoagulation methods. Similarly, advanced configurations such as slot-baffle designs—have demonstrated 62% energy savings and a 19% reduction in chemical consumption (Kizilaslan et al., 2019). Computational Fluid Dynamics models also show that tube settlers achieve removal efficiencies exceeding 67% for particles as small as 17 μm (Abeyratne et al., 2023). These findings emphasize the potential of tube settlers to improve both the physical and chemical quality of water while simultaneously lowering operational costs. However, several key aspects remain not fully understood (Fraji et al., 2013). While previous studies have focused on turbidity and suspended solids removal, few have systematically evaluated the removal of biological contaminants such as microorganisms, protozoa, and algae under full-scale operational conditions (Ahmed et al., 2021; Nouri Dodaran et al., 2019). There is a lack of comparative analysis between tube settlers and conventional clarifiers in high-capacity treatment plants, especially in arid regions where optimizing water treatment processes is essential (Al-Dulaimi and Racoviteanu, 2018). While computational fluid dynamics simulations and laboratory-scale studies provide valuable insights, there is still a lack of full-scale assessments conducted in real-world conditions. It is essential to evaluate the performance of tube settlers under varying inflow conditions, which are common in arid regions, to ensure their long-term operational reliability and efficiency (Bhorkar and Nagarnaik, 2020). The objectives of this study are to evaluate the effectiveness of tube settlers in removing various physical, chemical, and biological contaminants, including turbidity, total suspended solids, iron, aluminum ions, and living microorganisms. And provides a thorough evaluation and real-world validation of sedimentation processes, offering practical insights for improving these processes and lowering operational costs. It also advances sustainable water treatment technologies by addressing existing knowledge gaps and providing experimental evidence from full-scale operations. Our findings offer actionable recommendations for policymakers and engineers aiming to enhance the efficiency and sustainability of large-scale water treatment facilities, particularly in water-stressed environments.

2. Materials and methods

This research is an experimental study was conducted at the Babashiekhali water treatment plant in Isfahan, Iran (51.181°N, 33.387°E). The plant has a maximum treatment capacity of 1,000,000 m^3/day and operates through a multi-stage process comprising water intake, pretreatment, screening, coagulation- flocculation- sedimentation (accelerator clarifier), filtration, and disinfection. This study examined two circular clarifiers at the facility. Each backwash cycle utilized three 75 kW pumps, with a total of eight cycles per sand filter throughout the study period. Additionally, a 200 kW blower was employed during each backwash cycle to enhance filter cleaning. Figure 1 shows the location of the tube settler groups installed within the accelerator clarifier. The tube settlers in the clarifiers constructed from food-grade polypropylene (PP) and featured a honeycomb structure with a hexagonal cross-section. Each clarifier contained 350 tube settlers, with individual dimensions of 174 cm $\times$ 45 cm $\times$ 90 cm and a volume of 0.7 m^3. The hydraulic diameter of the tube settlers ranged from 50 mm to 80 mm, and they were installed at an inclination angle of 60° to enhance sedimentation efficiency. The sand filters associated with the clarifiers had a surface area of 116.5 m^2 per filter and an operational capacity ranging from 720 to 900 m^3/hr, with water velocities between 6.18 and 7.73 m/hr. Each sand filter measured 7 m (width) $\times$ 16.6 m (length) $\times$ 4 m (depth) and covering two primary filtration layers: a 60 cm-thick quartz layer with a particle size of 0.7 to 1.2 mm and a 50 cm-thick anthracite layer with particle sizes ranging from 1.4 to 2.5 mm.

Ten sand filters with the features shown in Table 1, were connected to the effluent of the two clarifiers (1 and 3) equipped with tube settlers, while another ten sand filters were linked to the effluent of the two clarifiers (2 and 4) without tube settlers. This configuration allowed for a direct comparison between clarifiers that have tube settler installations and those that do not. The total frequency of backwashing events was systematically recorded for each sand filter

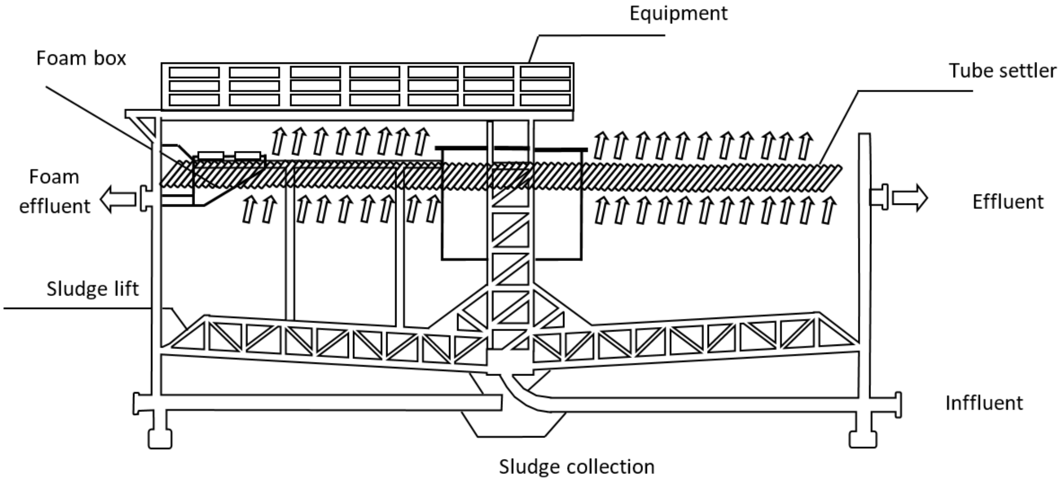

Figure 1. Schematic representation of the accelerator clarifier showing the location of the tube settler groups within the water treatment plant in Babashiekhali, Isfahan, Iran.

throughout the study. Electrical energy consumption during backwashing was measured for each event and then multiplied by the total number of backwashes to determine the cumulative energy usage for both clarifier systems. A total of 219 samples were collected daily for physical and chemical analysis, while an additional 65 samples were gathered for biological analysis over the 12-month operational period of the tube settlers. This comprehensive sampling strategy ensured the capture of seasonal variations and operational fluctuations. To ensure consistency and improve reliability, three samples were collected weekly from each clarifier.
The parameters analyzed included total suspended solids, Al^{3+}, Fe^{3+}, and some of biological indicators such as algae, diatoms, rotifers, and protozoa. These parameters were selected due to their critical role in evaluating the performance of the clarification process and were measured in accordance with the standardized procedures outlined in *Standard Methods for the Examination of Water and Wastewater* (Baird et al., 2017). The most commonly used method for total suspended solids is the Gravimetric Method, which involves filtration and drying. For turbidity measurement, the device emits light, usually from an LED or laser, and detects the scattered light. The result is displayed in NTU. Spectrometric and phenanthroline methods were used to measure iron and aluminum ions, respectively (Lipps et al., 2023). A comparative assessment was conducted between the clarifiers equipped with tube settlers and those without, allowing for an evaluation of the tube settlers' influence on water quality and operational efficiency. This comparative analysis aimed to identify differences in sediment removal efficiency, biological contamination levels, and energy consumption. Statistical analyses, including correlation tests, were performed using SPSS version 26 to explore relationships between the measured variables and to assess the significance of differences between the two clarifier systems. This rigorous analytical approach provided a comprehensive evaluation of the tube settlers' impact on clarifier performance and overall water treatment efficiency.

Table 1. Dimensions and operational characteristics of the tube settlers and sand filters used in the water treatment plant.

Parameters	Definition/amount
The hydraulic diameter of the tube settler	50-80 mm
Installation angle of tune settler	60°
The number of tune settler for each clarifier	350
Tube settler dimensions	174 × 45 × 90 cm
Tube settler volume	0.7 m^3
Surface for each sand filter	116.5 m^2
Capacity for each sand filter	720-900 m^3/hr
Water velocity in the sand filter	6.18-7.73 m/hr
Dimension of each sand filter (width, length, depth)	7 × 16.6 ×4 m
The thickness of the quartz layer in sand filters	60 cm
Quartz graining in sand filters	0.7-1.2 mm
Anthracite layer thickness in sand filters	50 cm
Anthracite graining in sand filters	1.4-2.5 mm

3. Results

The use of tube settlers in clarifiers significantly improved the removal efficiency of both chemical and biological parameters. The mean turbidity and TSS in the raw water were 31.14 NTU and 84.19 mg/L, respectively. The application of tube settlers reduced water consumption during backwashing by 25.90% and decreased electrical energy usage by 43.03%, highlighting the operational efficiency of the modified clarifiers. As shown in Table 2, clarifiers equipped with tube settlers (clarifiers 1 and 3) demonstrated lower concentrations of Al^{3+} and Fe^{3+} in the effluent compared to those without tube settlers (clarifiers 2 and 4). The mean Al^{3+} concentration was 37.67 ± 16.59 mg/L in the clarifiers with tube settlers, which is lower than the 55.18 ± 19.80 mg/L observed in the clarifiers without tube settlers. Similarly, Fe^{3+} levels decreased from 0.017 ± 0.005 mg/L in the clarifiers without tube settlers to 0.013 ± 0.004 mg/L in those with tube settlers.

Biological analysis further revealed notable differences in microorganism concentrations between the two systems. The mean diatom concentration was 511.23 ± 730.47 No/L in the clarifiers with tube settlers, representing a reduction compared to 720.09 ± 1227.08 No/L in clarifiers without tube settlers. Nematode concentrations were also lower in clarifiers with tube settlers (7.74 ± 5.83 No/L) than in those without (13.54 ± 8.96 No/L). Similarly, rotifer concentrations decreased from 10.38 ± 7.30 No/L in clarifiers without tube settlers to 6.66 ± 4.39 No/L in those with tube settlers. Protozoa concentrations were slightly lower in the clarifiers with tube settlers (7.49 ± 3.05 No/L) compared to those without (7.67 ± 3.19 No/L). Algae concentration also decreased from 598.07 ± 209.78 No/L in the clarifiers without tube settlers to 492.24 ± 187.90 No/L in those with tube settlers. The standard deviations for the measured variables were consistently lower in the clarifiers with tube settlers, indicating more stable and consistent effluent quality. Notably, the range of values for diatoms and algae was significantly broader in clarifiers without tube settlers.

Table 3 presents a comprehensive comparison of the removal efficiency across various parameters between the conventional clarifiers and the Super clarifiers that are equipped with settler tubes. The comparison was conducted using an independent t-test to assess the differences in performance between the two clarifier types. The results reveal significant differences across all measured variables, highlighting the distinct efficiencies of the two clarifier types. Notably, clarifiers with settler tubes (super clarifiers) demonstrate a significantly higher efficiency in removing both turbidity and TSS compared to conventional clarifiers.

A comprehensive analysis of the mean number of backwashes per day (as presented in Table 3) demonstate a statistically significant difference between the clarifier equipped with a settler tube (Clarifier 1) and the clarifier without the tube settler (Clarifier 2), with a p-value of 0.01. The data indicates that Clarifier 2 (without the settler tube) requires a significantly higher number of backwashes on average compared to Clarifier 1 (with the settler tube). Figure 2 visually illustrates this difference, showing the annual variation in the average number of backwashes for both clarifiers. This suggests that the presence of the settler tube may reduce the need for frequent maintenance, potentially enhancing the operational efficiency of Clarifier 1.

In terms of energy consumption, the independent t-test results reveal a substantial disparity between the two clarifier types, with a p-value of < 0.01. The data shows that Clarifier 2 consumes significantly more energy than Clarifier 1, indicating that the absence of the settler tube may lead to higher energy requirements, possibly due to less efficient solid-liquid separation. Figure 2 further illustrates the variation in energy consumption between the two clarifiers

Table 2. Statistical summary of chemical and biological variables in clarifiers with and without tube settlers.

Type of clarifier	Variables	Mean	SD	Maximum	Minimum	Range
With Tube settlers (clarifiers 1,3)	Al^{3+} (mg/L)	37.67	16.59	99.28	25.00	74.28
	Fe^{3+}(mg/L)	0.013	0.004	0.02	0.01	0.01
	Diatom (No/L)	511.23	730.472	3916	45	3871
	Nematod (No/L)	7.74	5.83	34.00	1.00	33.00
	Rotifer (No/L)	6.66	4.39	19.00	2.00	17.00
	Protozoan (No/L)	7.49	3.005	14.00	3.00	11.00
	Algae (No/L)	492.24	187.90	825	128.00	697.00
Without Tube settler (clarifiers 2, 4)	Al^{3+} (mg/L)	55.18	19.80	99.42	7.50	91.92
	Fe^{3+} (mg/L)	0.017	0.005	0.03	0.01	0.02
	Diatom (No/L)	720.09	1227.08	7832	120	7712
	Nematod (No/L)	13.54	8.96	52.00	3.00	49.00
	Rotifer (No/L)	10.38	7.30	31.00	3.00	28.00
	Protozoan (No/L)	7.67	3.19	14.00	3.00	11.00
	Algae (No/L)	598.07	209.78	910.00	205.00	705.00

Table 3. Comparison of removal efficiency, backwash frequency, energy consumption, turbidity, and TSS between conventional clarifiers (Clarifier 2) and super clarifiers equipped with settler tubes (Clarifier 1) based on independent t-test results.

variables	Mean difference	t	df	p-value
Backwash	-4.13	-20.86	436	0.001
Turbidity	1.21	4.72	436	0.001
Energy saving	-204.10	-35.62	436	0.001
TSS	1.21	4.72	436	0.001
TSS removal efficiency	-12.81	-7.12	436	0.001
Turbidity removal efficiency	-15.19	-8.82	434	0.001

throughout the year, with Clarifier 2 consistently exhibiting higher energy usage. This highlights the potential energy savings that can be achieved by using super clarifiers with settler tubes. The turbidity levels in the effluent of the two clarifiers were also significantly different, as indicated by the independent t-test (p-value < 0.01). The average turbidity in the effluent of Clarifier 2 was substantially higher than that of Clarifier 1, confirming that the presence of a settler tube in Clarifier 1 leads to more effective removal of suspended particles. Figure 2 provides a visual comparison of the effluent turbidity levels from both clarifiers, illustrating the marked difference in performance. Similarly, the TSS concentrations in the effluent showed a significant difference between the two clarifiers (p-value < 0.01). Clarifier 2 exhibited significantly higher TSS concentrations in its effluent compared to Clarifier 1, further supporting the finding that the settler tube enhances the clarification process. Figure 2 displays the variation in TSS levels throughout the year, reinforcing the superior performance of the super clarifier in reducing suspended solids.

Table 4 presents the results of the Pearson correlation analysis, examine the relationships between turbidity and TSS for both Clarifier 1 and Clarifier 2. The analysis reveals a significant positive correlation between turbidity and TSS

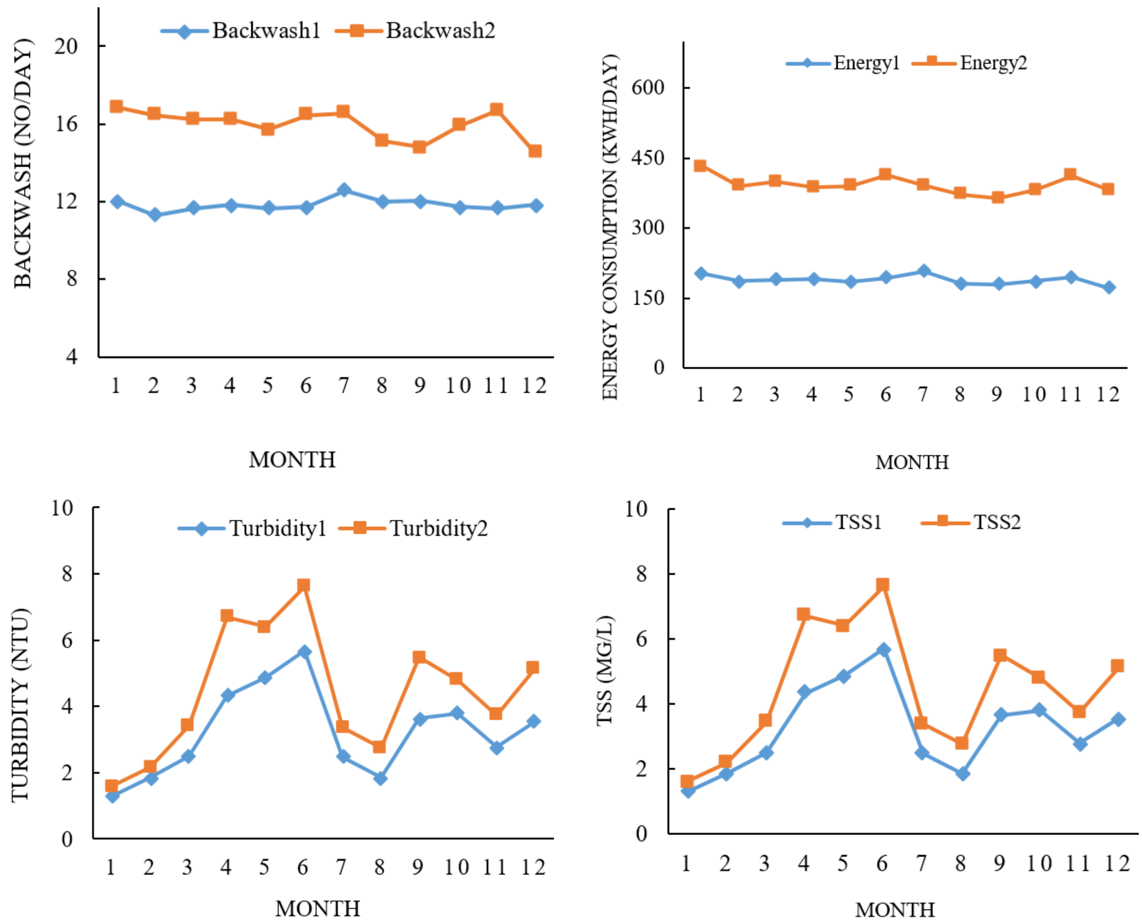

Figure 2. Annual comparison of the average number of backwashes, energy consumption, turbidity, and TSS levels for Clarifiers 1 (with settler tube) and 2 (without settler tube).

in both types of clarifiers, with p-values < 0.05 for each. This indicates that, in both clarifiers, increases in turbidity are closely associated with higher TSS concentrations in the effluent. The consistent correlation between these two variables underscores the importance of turbidity as a reliable indicator of suspended solids in the clarified water.

Table 4. Pearson correlation analysis between turbidity and TSS for both types of clarifiers (Clarifier 1 and Clarifier 2).

	TSS (1, 3)			TSS (2, 4)		
	r	p	n	r	p	n
Turbidity (1,3)	1	0.001	219			
Turbidity (2,4)	–	–	–	1	0.001	219

4. Discussion

4.1 Enhanced water treatment efficiency with tube settlers

The integration of tube settlers into accelerator clarifiers led to notable enhancements in water treatment efficiency, including reduced operational costs and improved contaminant removal effectiveness. A key finding of this study was the substantial reduction in the frequency of backwashing. The tube settler-equipped clarifiers required 25% fewer backwashes compared to their conventional counterparts, directly decreasing water consumption for sand filter backwashing. This operational advantage not only conserves a valuable resource but also enhances the sustainability of the water treatment process, a factor of paramount importance, particularly in water-scarce regions. Furthermore, the study revealed a remarkable 43% reduction in electrical energy consumption during the backwashing process. This significant energy saving is primarily attributed to the enhanced sedimentation efficiency of the tube settler-equipped clarifiers, which lessens the demand for energy-intensive filtration and backwashing cycles. This aligns with studies like Hanifa et al. (2021) and Kizilaslan et al. (2019), numerous reports indicate similar energy savings, suggesting a consistent trend across various implementations.

4.2 Enhanced chemical contaminant removal

The enhanced performance of clarifiers equipped with tube settlers resulted in better removal of chemical contaminants. Significant improvements in chemical removal efficiencies were observed (Mousavi Moghanjooghi et al., 2022). Turbidity and TSS, critical water quality parameters, were removed more effectively in the tube settler-equipped clarifiers. Turbidity, a measure of water clarity, was notably reduced in the effluent, achieving a maximum removal efficiency of 63%. This result clearly indicates that tube settlers enhance the sedimentation process, promoting superior particle removal and leading to clearer, higher-quality treated water. This high removal efficiency is consistent with the range reported in the literature, such as Hanifa et al. (2021), where conventional clarifiers with tube settlers achieved up to 94.6% turbidity removal. The difference in maximum removal efficiency between this study and Hanifa et al. (2021) may be attributable to variations in influent water quality, tube settler design parameters, or operational conditions. Similarly, the study demonstrated significant improvements in the removal of Al^{3+} and Fe^{3+} ions, common water treatment contaminants often introduced through coagulation processes. The average concentration of these metals was significantly lower in the effluent from the tube settler-equipped clarifiers compared to conventional clarifiers, demonstrating the efficacy of the tube settler system in removing chemical contaminants and improving overall water quality. This finding is consistent with. Fouad et al. (2016), who also showed that tube settlers significantly enhance the removal of iron and aluminum ions, likely due to improved coagulation and flocculation processes within the tube settlers.

4.3 Biological contaminant removal and challenges

The impact of tube settlers on biological contaminant removal was also investigated, comparing the removal efficiencies of diatoms, nematodes, rotifers, protozoa, and algae. Tube settlers improved removal efficiencies for diatoms, nematodes, and algae, although protozoa removal was less effective. These findings corroborate previous research indicating that tube settlers excel at removing larger, heavier particles like diatoms and algae, as these organisms are more readily settled due to their size and density. This aligns with Hassan and Hassan (2011), who observed that tube settlers were particularly effective at removing phytoplankton algae. The higher settling velocities of these larger organisms within the inclined tubes likely contribute to their enhanced removal (Safari et al., 2023). However, the study also confirmed that tube settlers may be less effective for smaller, lighter organisms such as protozoa, which can be more challenging to remove through sedimentation alone. This is consistent with findings from Fouad et al. (2016) and Omarova et al. (2018), who reported that smaller organisms like protozoa are not effectively captured by tube settlers, likely due to their lower density and size, which makes them less susceptible to gravitational settling. Nevertheless, the tube settlers demonstrated an overall improvement in biological contaminant removal, as evidenced by lower microorganism concentrations in the effluent from the modified clarifiers.

4.4 Statistical validation and operational benefits

Statistical analyses, including independent t-tests and Pearson correlation coefficients, further validated these findings. Significant differences in mean turbidity and TSS removal efficiency were observed between the two clarifier types, with tube settler-equipped clarifiers consistently outperforming conventional clarifiers. These statistically significant results provide strong evidence for the positive impact of tube settlers on water quality. The correlation analysis showed a strong positive relationship between turbidity and total suspended solids (TSS) levels in both types of clarifiers. This indicates that the tube settler systems were particularly effective in co-removing suspended solids and turbidity, which further improved the clarity and quality of the treated water. This study highlights the substantial benefits of integrating tube settlers into conventional water treatment systems. The reduced backwash frequency and lower energy consumption observed in the tube settler-equipped clarifiers are directly attributable to the enhanced sedimentation efficiency of the tube settler system. By increasing the settling area within a compact design, tube settlers facilitate more efficient particle settling, thus reducing the frequency and intensity of backwash cycles. This reduction not only conserves water, a crucial consideration in many regions, but also yields operational cost savings, particularly in energy usage, which often represents a major operational expense for water treatment plants. The 43% energy savings observed in this study are particularly significant, especially in facilities with frequent backwashing and high energy consumption. This magnitude of energy savings underscores the potential of tube settlers to significantly reduce operational costs. Therefore, tube settlers offer both environmental (water and energy conservation) and economic advantages, presenting a promising solution for sustainable water treatment.

4.5 Mechanisms of improvement and literature support

The improved chemical contaminant removal, particularly for turbidity and TSS, is directly attributable to the increased settling area provided by the tube settlers. The inclined tube design reduces particle upward velocity, enabling more efficient settling of larger particles and preventing short-circuiting within the clarifier. This design is particularly advantageous for removing turbidity, which is often associated with fine suspended solids that are difficult to remove in conventional clarifiers. This aligns with research by Fujisaki and Terashi (2007) and Shammas and Wang (2015), which has demonstrated that inclined tube settler designs reduce short-circuiting and improve overall water treatment performance. Short-circuiting, where water flows quickly through the clarifier without adequate settling time, is a common problem in conventional clarifiers. The tube settlers mitigate this issue by providing a more controlled flow path. The improved removal of Al^{3+} and Fe^{3+} ions supports the hypothesis that tube settlers enhance physical and chemical water treatment by improving coagulation and flocculation processes, leading to better particle aggregation and sedimentation. The tube settlers create a more quiescent settling environment, allowing for the formation of larger, more readily settleable flocs.

The enhanced biological contaminant removal observed in this study is consistent with previous findings that tube settlers are effective at removing microorganisms such as diatoms, nematodes, and algae. The effectiveness of tube settlers in removing these larger, denser organisms can be attributed to the higher sedimentation velocity within the inclined tubes, which allows for more effective gravity separation. However, the lower removal efficiency for protozoa may be due to their relatively lower density and the inability of tube settlers to efficiently settle smaller, less dense particles. This finding suggests that while tube settlers significantly improve the removal of certain biological contaminants, additional treatment methods, such as membrane filtration or UV disinfection, may be necessary to target microorganisms that are more challenging to settle. This is further supported by Fujisaki and Terashi (2007), who suggested that protozoa are generally more resistant to conventional coagulation and flocculation, often requiring additional treatment steps.

4.6 Implications and future research

The statistical significance of the differences between the two types of clarifiers, as indicated by the t-tests, further emphasizes the superior performance of the tube-settler-equipped clarifiers in removing both physical and chemical contaminants. The strong Pearson correlation between turbidity and TSS in both clarifier systems further supports the notion that these two parameters are closely linked, and the efficiency of the tube settler system in removing both is highly significant. This correlation shows that better turbidity removal is closely linked to improved TSS removal, highlighting the effectiveness of tube settlers in achieving superior overall water quality. The implications of this study are significant. The demonstrated improvements in water treatment efficiency, coupled with reduced operational costs and enhanced sustainability, position tube settlers as a valuable technology for both upgrading existing water treatment plants and designing new facilities. The reduced reliance on energy-intensive backwashing is particularly relevant in regions facing energy shortages or high electricity costs. Furthermore, the improved removal of turbidity and other contaminants contributes to improved public health outcomes by providing cleaner and safer drinking water.

Future research should focus on optimizing the design of tube settlers to enhance the removal of protozoa. Exploring different tube geometries, inclination angles, and materials could potentially enhance the capture of these smaller organisms. Additionally, investigating the long-term performance of tube settlers under varying raw water quality conditions is crucial for understanding their real-world applicability. Studies examining the impact of seasonal variations in temperature, turbidity, and organic matter content would be particularly valuable. Finally, research into hybrid treatment systems that combine tube settlers with other technologies like membrane filtration or UV disinfection could lead to more comprehensive and robust water treatment solutions.

5. Conclusion

The results of this study provide strong evidence for the effectiveness of tube settlers in boosting water treatment efficiency, particularly in terms of turbidity removal, TSS reduction, energy savings, and reduced backwashing frequency. These findings contribute to the growing body of literature supporting the use of tube settlers in enhancing the performance of conventional clarifiers, especially in regions facing water scarcity and high operational costs. While further studies are needed to optimize the performance of tube settlers for all types of contaminants, particularly protozoa, the results presented in this study indicate that tube settlers offer a promising solution for improving the efficiency and sustainability of water treatment plants. Future studies should address the identified limitations, specifically focusing on enhancing protozoa removal through design modifications or integration with other treatment technologies, and investigate the long-term performance and applicability of tube settlers under diverse raw water quality conditions. These results will be crucial for maximizing the potential of tube settlers as a key component of sustainable and cost-effective water treatment strategies.

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Authors contributions

Formal analysis and Investigation: M. M., and M. A. Methodology; M. M., M. A and P.N.; Software: M. M; Supervision: M. A. and P.N.; Writing: M. M., M. A., M. H., and P. N ; Writing-review & editing: M.H.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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