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Technical comparison between two pretreatment piping compact units for ultrafiltration water plants

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Abstract

Background: Ultrafiltration plants are increasingly used for producing high-quality water. The research aimed to compare two compact piping units employed as pretreatment systems to enhance surface water quality. The aim was to achieve the specified average values of feed water quality necessary for ultrafiltration (UF) plants, as per the requirements of the UF manufacturer. The units were intended for use in a water treatment plant with a capacity of 5000 m^3/day, where the influent water's total suspended solids (TSS) ranged from 130 to 160 mg/L.

Methods: The initial unit implemented plate settler technology to facilitate sedimentation, whereas the subsequent unit adopted filtration. Both piping systems were assessed for their efficacy in conforming to stipulated water quality standards alongside the corresponding economic considerations.

Results: Both piping units effectively achieved the mandated water quality standards, albeit at disparate costs. In this specific case study, the sedimentation units incurred an initial expense of 191 800 Egyptian pounds (LE) (equivalent to $6209.5), whereas the filtration units necessitated an initial investment of 471 680 LE ($15 270.5). Additionally, both the initial outlay and ongoing operational expenses of the sedimentation units were inferior to those of the filtration units.

Conclusion: Based on the study results, the use of sedimentation units proved to be more cost-effective. Despite meeting the required water quality standards, the sedimentation units had lower initial and operational costs than the filtration units. Therefore, it is recommended to use sedimentation units as the pretreatment system in this water treatment plant to achieve the desired water quality while optimizing costs.

Keywords: Ultrafiltration, Freshwater, Sediments, Water purification, Water quality

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Introduction

In recent times, several new water purification techniques have emerged as alternatives to conventional water purification plants. These techniques include methods such as the Dyna sand system and ultrafiltration (UF) system. These techniques offer numerous advantages over traditional methods, particularly UF plants. One of the key advantages of water purification plants utilizing the UF system is their compact size and ease of installation. Compared to conventional plants, these units require minimal space and can be constructed relatively quickly. In this type of plant, only electrical buildings, water tanks, and UF containers containing the UF modules and necessary equipment are needed. Another significant advantage of UF plants is the high quality of the treated water they produce. Regardless of the initial quality of the inlet water, these plants consistently deliver superior effluent water (1).

In recent times, Egypt has witnessed the installation of several UF plants, primarily due to limited available space for constructing water treatment facilities, especially in rural areas. However, many of these plants encountered a common issue of producing a capacity lower than their designed capacity. This problem arose due to the poor quality of water sources in Egypt, particularly in rural areas, where high levels of pollutants significantly affect water quality.

While UF modules can effectively treat such poor water quality without compromising the outlet quality, they are susceptible to membrane fouling. Fouling occurs when particles accumulate either on the membrane surface or within the membrane pores (2). This fouling leads to reduced flux, higher trans-membrane pressure, increased frequency of backwashing and chemical cleanings, and a shortened lifespan of the UF modules. Consequently, the operational costs of these plants increase (2).

To mitigate these challenges and maximize the benefits of UF plants, a necessary step in the treatment process is the implementation of a compact pretreatment unit. This unit should be small in size, easy to construct, and cost-effective to install. Its primary purpose is to reduce the influent loads to the UF modules and ensure that the inlet water quality falls within the acceptable range as stipulated by the manufacturer (3,4).

Among the crucial factors influencing the influent water quality is the concentration of total suspended solids (TSS). According to the manufacturer's requirements, the inlet water should have a TSS concentration ranging from a minimum of 50 mg/L to a maximum of 100 mg/L. By implementing a well-designed pretreatment unit, the advantages of UF plants can be preserved, ensuring efficient and reliable water treatment while minimizing operational challenges.

The selection of the pretreatment action is influenced by several factors, including the type of feed water, membrane properties, and operating conditions (5). Various types of actions can be employed, including physical, chemical, biological, or a combination thereof (6). Among the commonly used pretreatment processes are coagulation, sedimentation, bio-filtration, adsorption, and oxidation (7,8). While membrane technology, such as microfiltration, can be utilized as a pretreatment method, it is generally not recommended due to its high cost.

Coagulation can be employed as a standalone in-line process with low coagulant doses or as a precursor to sedimentation or filtration processes with higher coagulant doses, resulting in improved efficiency (9). In-line coagulation offers the main advantage of simplicity; however, determining the appropriate coagulant dosage for this operation can be challenging. In the case of in-line coagulation, the jar test, a common method for determining optimal coagulant dosage, does not provide significant benefits (10).

There are many studies made to compare the coagulation followed by sedimentation and in-line coagulation. Park found that in-line coagulation was more effective than coagulation followed by sedimentation in improving membrane performance when treating surface water (11).

Based on the study conducted by Liang, which compared three pre-treatment processes (in-line coagulation, coagulation followed by sedimentation, and coagulation followed by sedimentation followed by filtration) for treating surface water with high algae content, coagulation followed by sedimentation was found to be the most effective in improving membrane performance and reducing membrane fouling (12).

According to the study conducted by Moon, which compared direct UF with the coagulation followed by the sedimentation process, the results demonstrated that coagulation followed by sedimentation yielded higher production efficiency and reduced fouling (13).

Filtration is commonly used as a pretreatment process for UF and can involve different mechanisms such as physical sieving or chemical adsorption/deposition, depending on the media used (14).

Sand, anthracitic coal, and activated carbon are among the most commonly used media in filtration processes for pretreatment. These media can effectively remove suspended particles, turbidity, and certain dissolved substances from the water. There are other types of filter media used in filtration processes, including carbon steel, stainless steel, string-wound polyester, and fabric cloth (15,16). However, the interactions between these less common media types and aquatic particles require further research to understand their filtration process and performance better.

Peldszus conducted a study using bio-filtration as a pretreatment for UF membranes in surface water treatment. The results showed that membrane fouling was reduced by removing protein-like substances that caused reversible and irreversible fouling. These substances interacted with other particles, forming combined fouling layers (17).

Similar findings were obtained by Filloux, who also observed that bio-filtration effectively reduces both reversible and irreversible fouling (18).

Mosqueda-Jimenez conducted a study comparing the efficiency of using UF alone versus using bio-filtration as a pre-treatment for UF in treating surface water. The results showed that UF without pre-treatment had higher efficacy in reducing Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC) content due to the formation of a larger cake layer that aided in organic removal. However, combining bio-filtration and UF achieved a greater reduction in membrane fouling and higher flux rates. The choice between the two approaches depends on specific water treatment goals and priorities (19).

Several studies conducted by Wend, Persson, Huang, and Velten have reported similar results to the aforementioned findings when utilizing bio-filtration as a pre-treatment for UF membranes (20-23). These studies support the notion that bio-filtration applied before UF can effectively reduce membrane fouling and enhance overall filtration performance.

Lipp et al. conducted a study on the combination of coagulation and sand filtration as a pre-treatment for UF membranes. Their results indicated an improvement in turbidity removal efficiency (23).

Similarly, Weilenmann et al obtained similar results when investigating the combination of bio-filtration and coagulation as a pre-treatment for UF (23). Their findings demonstrated enhanced turbidity removal efficiency, further supporting the effectiveness of combining these pre-treatment methods.

Howard found that biofiltration as pretreatment reduced UF fouling by lowering turbidity, biopolymer, and humic concentrations. Adding low coagulant doses in-line improved the effectiveness of biofiltration in reducing membrane fouling (24).

Pramanik reported that biological pre-treatments like biological aerated filter (BAF) and sand filter effectively reduced organic components, particularly carbohydrates, improving UF membrane filterability. Also, BAF showed the greatest improvement in flux due to the effective breakdown of high molecular weight organics, while coagulation processes were less effective in removing biofouling potential components (25).

Nagy et al developed compact piping units using sedimentation and filtration processes and demonstrated their effectiveness in producing high-quality water suitable for UF membrane influent (26,27).

The efficiency of these compact units depends on factors such as sedimentation retention time, filtration media, and feed water characteristics.

In light of the findings from previous studies, the present study aimed to compare the performance of sedimentation and filtration compact piping units as pretreatment options for surface water before it enters UF modules. The comparison will likely consider factors such as water quality improvements, turbidity removal efficiency, reduction in membrane fouling, and overall effectiveness of the pretreatment process. This study was conducted on a case-by-case basis and specific quality water source, so the results may not be applicable to other water sources.

Materials and Methods

To compare the two pretreatment units for the filtration process and sedimentation process, a technical analysis will be conducted based on their process efficiency and financial implications. The study is divided into two main parts.

Selection of the pretreatment type: In the first part, the goal is to determine the most suitable pretreatment type for the case study. The available experimental results from studies Nagy et al (26,27) will be used for this purpose. These results should provide information on the performance and effectiveness of the pretreatment units in terms of removing TSS from the influent water (26,27).

Data collection and cost estimation: The second part involves collecting data and estimating costs for both pretreatment units. This includes determining the initial capital cost as well as the operational expenses (running cost) associated with each unit. The cost estimation should take into account factors such as equipment, installation, maintenance, energy consumption, and any other relevant expenses. This process was done by financial experts in the field of water treatment plants in Egypt.

Furthermore, since the case study pertains to a water treatment plant with a capacity of 5000 m^3/day and an influent water TSS concentration ranging between 130 to 160 mg/L, the sizing of each unit will be performed based on these parameters. The estimated total cost for each unit will then be calculated to facilitate a comprehensive financial comparison between them.

Table 1. The TSS concentration and removal efficiency according to the pretreatment used

Pre-treatment type	TSS concentration (mg/L)	Removal rfficiency (%)
Sedimentation RT (30 min)	3.90	97.33
Sedimentation RT (15 min)	10.42	92.87
Sedimentation RT (5 min)	20.30	86.10
Sedimentation RT (20 sec)	52.72	63.89
Mono filtration using sand	62.50	57.19
Mono filtration using anthracite coal	65.42	55.19
Mono filtration using rice straw	74.18	49.19
Dual filtration using sand and anthracite coal	19.77	86.46
Dual filtration using sand and rice straw	31.10	78.70
Dual filtration using anthracite coal and rice straw	33.85	97.33
Triple filtration using sand, anthracite coal, and ice straw	9.67	92.87

TSS: Total suspended solids; RT: Retention time.

Table 1 should provide information on the outlet TSS concentration results and the removal efficiency achieved by each of the pretreatment methods previously used by other researchers (24,25). The influent water TSS concentration was 146 mg/L. This data will serve as a basis for evaluating the effectiveness of the pretreatment units in terms of TSS removal.

Results

Based on the provided information, it appears that both sedimentation and filtration units are capable of achieving the required water quality for the given water quality conditions.

For the sedimentation unit, a minimum velocity of 0.3 m/min is specified. This velocity is considered sufficient to achieve the desired water quality, indicating that the sedimentation process can effectively remove the suspended solids within the influent water.

Regarding the filtration unit, it is stated that all of the used filtration media are capable of reaching the required water quality. This implies that the filtration process, regardless of the specific media employed, is effective in removing the suspended solids to meet the desired water quality standards.

Based on this information alone, it does not provide a clear advantage for one unit over the other in terms of achieving the required water quality. Therefore, further analysis considering other factors such as process efficiency, cost, and other relevant considerations will be necessary to determine the best choice between the sedimentation and filtration units from both a technical and financial standpoint.

For the sedimentation unit: Assume one unit with L = 6 m, D = 0.5 m, S = 0.02 m, plate thickness = 0.002 m.

Note: These assumptions may vary according to the available plant area and the arrangement of the units.

As described in Figure 1:

- L = N × S + (N-1) plate thickness
- N = (6 + 0.002)/(0.022) = 272 plate
- W = D = 0.5 m
- A = N × S × W = 272 × 0.02 × 0.5 = 2.72 m^2
- Assume sedimentation velocity = 0.3 m/min
- Q = V × A = 0.3 × 2.72 × 24 × 60 = 1175.04 m^3/day
- Volume of pipe = (3.14 × 0.5 × 0.5 × 6)/4 = 1.18 m^3
- T = 1.18/(1175.04/(60 × 24)) = 1.44 min
- No. of units to serve plant capacity 5000 m^3/day = 5 units

Where *Q* is discharge (m^3/day), *D* is pipe diameter (m), *A* is the sedimentation area, *L* is pipe length (m), *T* is retention time (day), *V* is sedimentation velocity (m/min), *N* is the number of spacing, *S* is spacing (m), and *W* is plate width (m).

According to the provided specifications, the sedimentation pilot for the water treatment plant consists of 5 unplasticized polyvinyl chloride (UPVC) pipes, each with a diameter of 50 cm and a length of 6 m. Each pipe is equipped with 272 smooth plastic plates inclined at an angle of 45° with the horizontal line. The distance between every two plates is 2 cm.

Additionally, there are three valves connected to the pipe system. The water inlet valve has a diameter of 150 mm, the water outlet valve has a diameter of 150 mm, and the sludge outlet valve has a diameter of 100 mm.

Figure 1 shows a schematic diagram for one of the sedimentation units.

According to the provided specifications, the filtration pilot for the water treatment plant consists of 30 UPVC pipes. Each pipe is divided into three parts, with each part having a diameter of 15 cm and a length of 0.6 cm. These parts can be utilized for mono, dual, and triple filtration processes.

To prevent the loss of media particles from the filter, two ends of each segment are covered by a double layer of gauze. This covering acts as a barrier to retaining the filter media within the system.

Additionally, there are two valves connected to the filtration pilot. The water inlet valve has a diameter of 150 mm, while the water outlet valve has a diameter of 150 mm.

Figure 2 shows the schematic diagram for one of the filtration units.

Table 2 shows the average costs for all used materials to create the pretreatment units according to the Egyptian commercial market.

Table 3 presents the computed expenses associated with the sedimentation units required to pre-treat the incoming water in this particular research scenario.

Table 4 presents the computed expenses associated with the filtration units required to pre-treat the incoming water in this particular research scenario.

It can examine the effluent TSS values for both the sedimentation and filtration techniques in Table 1. By comparing these values with the influent TSS values necessary for the UF module manufacturing process, you can assess their compatibility. Figure 3 demonstrates the TSS values obtained from the preceding tables, along with the minimum and maximum influent TSS values required for the UF modules.

Discussion

Table 2. The average costs for all used materials

Type	Description	Cost (LE)	Cost ($)
UPVC pipe	Ø 500 mm length 6 m	12000	388.5
UPVC pipe	Ø 150 mm length 0.6 m	360	11.65
Butterfly valve	Ø 150 mm	7500	243
Butterfly valve	Ø 100 mm	6000	194.5
Reducer	Ø 500/150 mm	2000	65
Plates	Special shape (0.5 × 0.3) m	5	0.2
Sand	1 m^3	200	6.5
Anthracitic coal	1 m^3	1250	40.5
Rice straw	1 m^3	50	1.65

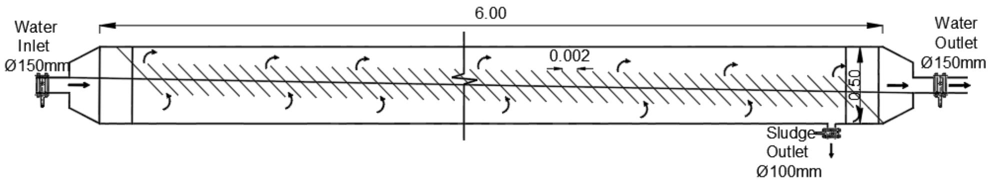

Figure 1. The schematic diagram for one of the sedimentation units

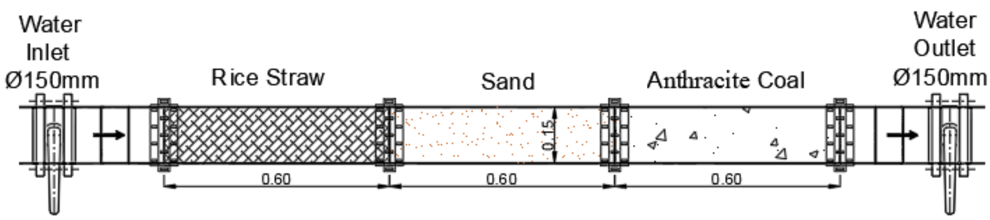

Figure 2. The schematic diagram for one of the filtration units

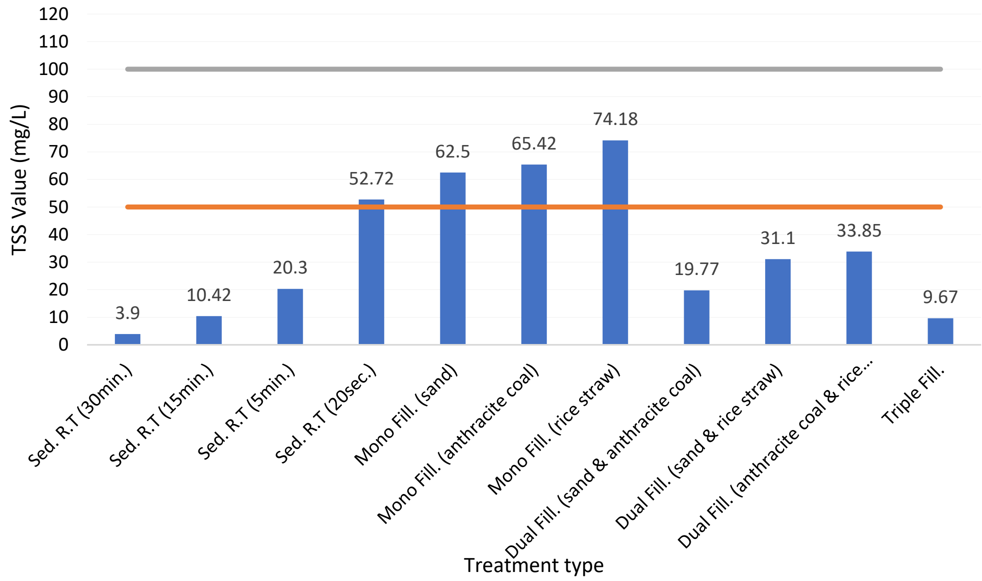

Figure 3. Effluent TSS values with the minimum and maximum TSS values for UF modules

Table 3. The estimated cost for the sedimentation units

Type	Number	Total cost (LE)	Total cost ($)
UPVC pipe Ø 500 mm length 6 m	5	60,000	1942.5
Butterfly valve Ø 150 mm	10	75,000	2428
Butterfly valve Ø 100 mm	5	30,000	971.5
Reducer Ø 500/150 mm	10	20,000	647.5
Plates special shape (0.5 × 0.3) m	1360	6,800	220
Total cost		191,800	6209.5

Table 4. The estimated cost for the filtration units

Type	Number	Total cost (LE)	Total cost ($)
UPVC pipe Ø 150 mm length 0.6 m	60	21,600	699.5
Butterfly valve Ø 150 mm	60	450,000	14569
Sand	0.32 m^3	64	2.1
Rice straw	0.32 m^3	16	0.5
Total cost		471,680	15270.5

The chart in Figure 3 can be a valuable tool in deciding the best model for sedimentation and filtration units. Analyzing the data it contains, along with considering other factors, will assist in making an informed decision about the most suitable models for your application.

Based on the information provided, the chart shows that all retention times for the sedimentation unit achieve TSS values below the minimum limit for the inlet TSS, except for the minimum retention time which slightly exceeds the minimum limit, it suggests that the sedimentation unit is effective in removing suspended solids.

In this case, choosing the minimum retention time can be considered the best economical choice because it achieves the required level of TSS removal while minimizing the dimensions of the unit. By selecting the minimum retention time, you can reduce the size and cost of the sedimentation unit while still meeting the desired water quality standards.

In contrast to the sedimentation unit, the data suggests that using dual and triple filtration units consistently achieves TSS values below the minimum limit for the inlet TSS. On the other hand, units utilizing mono filtration alone tend to result in TSS values that exceed the minimum limit.

Therefore, based on the provided information, it can be concluded that dual and triple filtration systems are more effective in removing suspended solids compared to mono filtration.

Based on the comparison of different filtration media, specifically anthracitic coal and sand, it has been observed that the effluent quality achieved with anthracitic coal as a filtration media in mono or dual filtration was similar to that of sand. However, the cost of anthracitic coal per kilogram is significantly higher than that of sand, based on the media prices in Egypt. Therefore, considering the cost factor, the use of anthracitic coal as a filtration media is not recommended.

Additionally, it has been noted that triple filtration achieved maximum efficiency, but such a high level of efficiency may not be necessary for a pretreatment unit. As a result, using triple filtration is not recommended as it would increase costs without providing significant additional benefits.

Considering both the cost-effectiveness and the required level of efficiency for a pretreatment unit, it is advisable to explore alternative filtration media that offer a more favorable cost-to-efficiency ratio. Sand, which has shown similar effluent quality to anthracitic coal, appears to be a more cost-effective option.

Also, it was observed that mono filtration using sand, mono filtration using rice straw, and dual filtration using both sand and rice straw can all reach the acceptable limits in terms of effluent quality while maintaining responsible costs.

However, it is noted that mono filtration using sand requires a higher rate of backwashing compared to mono filtration using rice straw and dual filtration using both media. This higher rate of backwashing increases operational costs and reduces the plant capacity. Therefore, mono filtration with sand is not recommended due to its higher operational costs and reduced efficiency.

On the other hand, rice straw is identified as the cheapest filtration media. However, mono filtration using rice straw may have lower removal efficiency for TSS than dual filtration. This suggests that using rice straw alone may not achieve the desired level of TSS removal.

Based on the information provided in Tables 3 and 4, the sedimentation unit is a more favorable choice for treating surface water before it enters the UF modules in a case study. This conclusion is based on two main factors, namely, initial costs and operational costs.

Firstly, it is mentioned that the initial cost of the filtration unit is significantly higher than that of the sedimentation unit. A lower initial cost for the sedimentation unit suggests that it is a more cost-effective option in terms of capital investment.

Secondly, operational costs are considered, and it is noted that the filtration unit requires higher operational costs due to the need for backwashing pumps to complete the filtration process. This implies that the sedimentation unit has lower operational costs, making it a more economical choice in terms of ongoing expenses.

Considering both the lower initial cost and lower operational costs of the sedimentation unit, it is reasonable to conclude that it is the best choice for treating surface water before it reaches the UF modules.

Conclusion

Based on the provided case study information, which includes a water treatment plant with a capacity of 5000 m^3/day and influent water with TSS ranging between 130 to 160 mg/L, the sedimentation piping unit using plate settler technology and the filtration piping unit are both viable options for efficient pretreatment of UF modules.

The sedimentation unit characterized by the shortest retention time emerges as the optimal selection among available sedimentation alternatives. This denotes that a reduced retention time during sedimentation yields satisfactory TSS removal efficacy for the influent water in this specific investigation.

Conversely, the dual filtration system employing sand and rice straw as filtration media is identified as the superior option among the filtration alternatives. This combined filtration setup attains elevated TSS removal efficiency in contrast to the sedimentation unit.

Nevertheless, it is imperative to factor in the cost aspect when concluding. Both the initial investment and ongoing operational expenses linked with the filtration piping unit notably surpass those of the sedimentation piping unit. Given this, the suggestion in this particular investigation leans towards utilizing the sedimentation piping unit.

The preference for the sedimentation unit over the filtration unit stems from the careful examination of cost variables. Despite the potential for the dual filtration system to deliver heightened TSS removal efficiency, the escalated associated expenditures render the sedimentation unit a more viable option for this precise case study.

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Conceptualization: Mohamed ElHosseiny El-Nadi.
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Supervision: Mohamed ElHosseiny El-Nadi.
Validation: Mohamed ElHosseiny El-Nadi.
Visualization: Mohamed ElHosseiny El-Nadi, Amira Mohamed Nagy.
Writing–original draft: Amira Mohamed Nagy.
Writing–review & editing: Mohamed ElHosseiny El-Nadi, Amira Mohamed Nagy.

Competing interests

The authors declare that they have no conflict of interests.

Ethical issues

The authors hereby certify that all data collected during the study are as stated in this manuscript, and no data from the study has been or will be published elsewhere separately.

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