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Performances of various hybrids systems coagulation–ultrafiltration/ nanofiltration-reverse osmosis in the treatment of stabilized landfill leachate

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ABSTRACT

To assist resolve issues associated with landfills which may pose a potential environmental threat via discharge of high strength polluted wastewater known as leachate, because of the huge amount of municipal solid waste dumped into landfills. A chain of processes for treating stabilized leachate or landfill leachate (LFL) at laboratory-scale and low costs will be investigated. The treatment system consists of the integration of ultrafiltration (UF) membrane process with coagulation method (Coag-UF) as pretreatment step for treating LFL using a dual nanofiltration (NF) and reverse osmosis (RO) system with the main objective to achieve the Moroccan discharge limits. The results show that the combination of Coag-UF, using ferric chloride $FeCl_3$ as a coagulant, has allowed a significant reduction of LFL pollutants, namely 62% for chemical oxygen demand, 89% for total suspended solids and 62% for iron (Fe) while reducing the fouling phenomena. Also, the results indicate that the Coag-UF/NF/RO hybrid system is able to produce quality water according to directive FAO and water reuse standard for irrigation, land watering in Morocco, with an overall water recovery up to 57.2%, a salt rejection reaches 99% and a low energy cost (0.0019 US $/m^3) compared to the two others hybrid systems Coag-UF/RO and Coag-UF/NF which their energy cost are 0.0044 and 0.0032 US $/m^3, respectively.

Keywords: Coagulation; Ultrafiltration; Nanofiltration; Reverse osmosis; Hybrids systems; Stabilized; Landfill leachate; Energy consumption

1. Introduction

Human activities affect greatly the generation of solid wastes. Today, landfilling still one of the least expensive methods for their disposal. After landfilling, solid waste undergoes physico-chemical and biological changes. Consequently, the degradation of the organic fraction of the wastes in combination with percolating rainwater leads to the generation of a high-strength contaminated liquid called leachate or landfill leachate (LFL) [1,2]. Leachate is a liquid, which is a mixture of organic and inorganic contaminants which are harmful for the environment [3,4]. Therefore, if it is not properly treated, it can lead to serious problems of groundwater/surface water contamination [5]. Accordingly, removal or reduction of contaminants to acceptable levels is imperative before discharging the LFL into receiver environment or for reuse. Indeed, discharge standards are becoming more stringent, and the scarcity of water, exacerbated in recent decades by global warming, make leachate treatment incentive in these conditions. LFL characteristics

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vary, as they depend mainly on landfill age as well as on climate conditions and the wastes landfilled [6,7].

Hence, in Morocco LFL treatment is currently a challenge that must be met especially as the quantities of LFL produced continue to increase especially, since waste sorting is still not done at the source. On the basis of LFL composition, many biological, chemical and physical methods are used alone and/or in combination to removing unwanted constituents from LFL. Biological processes are very effective in removing organic and nitrogenous matter from young LFL when the ratio of the 5 days biochemical oxygen demand (BOD_5) and the chemical oxygen demand (COD) (BOD_5/COD) has a high value (>0, 5). With time, easily biodegradable organic matter decreases and the presence of recalcitrant substances (mainly humic and fulvic acids) limit biological process's effectiveness [8,9]. Therefore, LFL obtained from old LFL requires combined physical and chemical processes [10–12]. Among these processes, coagulation–flocculation (Coag-Floc) remains the most communally employed method. Due its simplicity and high selectivity toward colloidal species [13,14]. It is principally recommended as pretreatment in the processing line of young LFL, or as post-treatment of partially stabilized LFL with low biodegradability, that is, low BOD_5/COD ratio (<0,1) [4]. Amokrane et al. [13] reported that conventional coagulants (aluminum sulphate, polyaluminum chloride, ferrous sulphate, and ferric chloride) generally remove 10%–25% of COD from young LFL and 50%–65% COD from stabilized LFL or biologically pretreated LFL. In addition, membrane-based separation processes, such as nanofiltration (NF) and reverse osmosis (RO), have been adopted as the polishing step by integrating the process of LFL treatment [15,16]. They may effectively remove residual contaminants and total dissolved solids (TDS) from LFL to reach levels of needed purification to meet the required standard. However, they are subjected to concentration polarization and membrane fouling leading to flux drop [17,18]. This phenomenon is a serious limitation, since it induces frequent stops and washing sequences to recover the initial permeability of the membranes [19,20]. Hence, membrane-based separation processes are not suitable as a single process in LFL treatment. However, to cope with temporal fluctuations of LFL composition, remove or reduce contaminating loads from LFL and improve the overall treatment efficiency, the combination of multistage treatments is essential. In this context, in a previous paper, Elfilali et al. [21] showed that combination of membrane bioreactor (MBR) and RO achieved a strong reduction in the polluting load of LFL. MBR process removed 85% and 76% of total suspended solids (TSS), BOD_5 and COD respectively. While the RO, at pressure vessel configuration, as downstream unit of MBR have reduced more than 95% of polluting organic matter and have retained 98% of TDS with a recovery above 84%, but it is limited by its operating cost. Previous studies have estimated the operating cost of MBR/RO hybrid systems [22] and MBR/NF/RO systems [23] for the treatment of LFL at 3.86 and 4.55 US$/m^3, respectively.

In the present paper, due to the type of LFL which is a stabilized LFL, it will be treated by the substituting the biological treatment with the chemical one which is the coagulation method. Moreover, NF will be included to further increase the volume of the treated effluent while minimizing the cost linked to the treatment using RO and increasing the membrane lifetime.

At the same time, many published researches have focused on treatment processes including Coag and/or NF and/or RO. JiaShin et al. [24] investigated the inline coagulation–ultrafiltration (Coag-UF) as the pretreatment for RO brine treatment and recovery using polyaluminum chloride (PACl), aluminum chlorohydrate (ACH) and ferric chloride ($FeCl_3$) as the coagulants. Liquid chromatography-organic carbon detector (LC-OCD) was used to characterize the dissolved organic carbon (DOC) fractions eliminated by inline Coag-UF. It illustrated that $FeCl_3$ shows higher removal efficiency for almost all the DOC fractions ranging from low to high molecular weight. Thus, due to its high DOC removal efficiency, in-line ($FeCl_3$)-UF coagulation is a potential pretreatment to reduce the downstream RO fouling tendency. Likewise, Rukapan et al. [25] investigated, at full-scale leachate treatment systems, the effect of chemical coagulation and (MF) microfiltration pretreatment on RO membrane fouling characteristics. The chemical coagulation pretreatment was carried out by $FeCl_3$ coagulation followed by sand filtration. Meanwhile, MF pre-treatment utilized direct filtration using a 0.03 μm membrane. The results showed that accumulated foulant on the RO membrane in MF pre-treatment were significantly lower than that of chemical coagulation. However, NaOH cleaning of the fouled RO membrane from the chemical coagulation pretreatment case was more effective recovering the permeate flux of RO membrane which explains the formation of a loose-structure cake layer compared to gel-like layer in the MF pretreatment case. Moreover, the study of the comparison of NF-RO and RO-NF for the treatment of mature LFL indicated that both NF and RO steps in NF-RO can operate at lower pressures compared to NF and RO stages in RO-NF. At the same operating conditions, individual stages in NF-RO provide higher water fluxes than those in RO-NF, proving NF-RO to be more energy efficient [26].

This study aims to investigate the performance comparison of hybrid system based on the combination of Coag-UF/NF/RO for Oum Azza LFL (Morocco) treatment. For this, the efficiency of the two types of coagulants such as aluminum sulfate (alum) and ferric chloride is examined in order to choose the most efficient in the pollution indicators abatement. Then, coagulation process will be followed by ultrafiltration (UF) step (Coag-UF) in order to minimize the fouling phenomenon for subsequent membrane separation. Next, compared performances of NF, RO and NF/RO dual membrane systems will be applied to provide advanced post-treatment of LFL. Finally, technico-economic performances of Coag-UF/NF/RO hybrid system are also investigated and discussed.

2. Experimental

2.1. LFL site

LFL used in this study, is collected from landfill technical center of Oum Azza. The site of Oum Azza is located in the Rabat-Salé-Kénitra (RSK) region about 30 km in the southwest of Rabat city (Capital of Morocco) and covers an area of 110 ha. Fig. 1 gives the map localization of Oum Azza landfill [27]. In 2007, Oum Azza was the only controlled landfill over the country. Nowadays, it receives almost 50,000 tons/y of household and similar waste (HSW) coming from 13 municipalities in the RSK region. These wastes are composed of more than 60% of very wet organic waste (50%–60% of water) and have a low calorific value of less than 900 kcal/kg [28]. It generates a large quantity of leachate and the estimated average is around 480 m^3/d [29]. The chemical physical characteristics of raw LFL and the Moroccan Rejection Standards are listed in Table 1.

2.2. Setup procedure treatment of LFL

The landfill leachate treatment procedure is a combination of the coagulation method and three different types of separation membranes. The first step presents the pretreatment step. It was composed of the integration of coagulation using $FeCl_3$ as the most efficient coagulant and the module UF to reduce the pollutant loading of LFL by removing suspended solids and colloids and therefore minimize the fouling phenomenon.

In the second step, the pre-treated leachate is stored in a tank to then be treated by a combined NF-RO system in order to purify it by removing both residual organic contaminants and salts. Fig. 2 shows a general diagram of the treatment process.

2.2.1. Coag-UF

The treatment of Oum Azza LFL is carried out by preliminary laboratory-scale coagulation tests using a jar test device. The system is equipped with six glassed beakers of one liter each, a magnetic stirrer, and mixing paddles. The beakers are aligned in a series pattern that contains mixing paddles regulated by a gauge of revolution per minute (rpm) fixed at stirrers center. Experiments are performed using ferric chloride $FeCl_3$ and aluminum sulphate $Al_2(SO_4)_3$ coagulants. Experiments are conducted at three different initial pH such as, initial pH of the LFL, pH = 7 and pH = 5 at various doses of coagulants between 0 and 20 g/L. Directly after the introduction of coagulant, the samples are rapidly mixed at 200 rpm during 3 min, followed by slow agitation at stirring speed of 45 rpm during 30 min, while the final settling step lasted for another 1 h. Thereafter, the supernatant is carefully collected and the indicators of pollution are analyzed in order to determine the efficiency of the operation.

Jar testing is based on pollutant removal ability and flocs settle-ability. This study will select the ideal coagulant (alum or $FeCl_3$) for this stage of LFL treatment. Then, the supernatant liquid collected from the coagulation tank obtained with the ideal coagulant is subjected to the integrated UF system. The UF membrane used is tubular with pore size of 20 nm.

2.2.2. Membrane experimental setup

NF and RO experiments are conducted on an industrial pilot NF/RO provided by TIA company (Applied

Table 1
Raw LFL characteristics and Moroccan Rejection Standards

Parameters	Average value	Discharges standards[a]
Color	Dark brown	–
pH	8.1 ± 1.5	5.5–9.5
Temperature (°C)	27 ± 0.6	30
E (mS/cm)	25.85 ± 4.9	2.7
COD (mg O_2/L)	6,209 ± 1,224	250
BOD_5 (mg O_2/L)	950 ± 276.6	120
TSS (mg/L)	397 ± 7	150
BOD_5/COD	0.17	–
TN (mg/L)	875 ± 150	40
TP (mg/L)	41.5 ± 12.3	15
Na^+ (mg/L)	3,293 ± 313.5	–
Cl^- (mg/L)	3,231 ± 215.25	–
Fe (mg/L)	12.6 ± 1.15	–

[a]Moroccan Pollution Standards specific limits for municipal discharge [30].

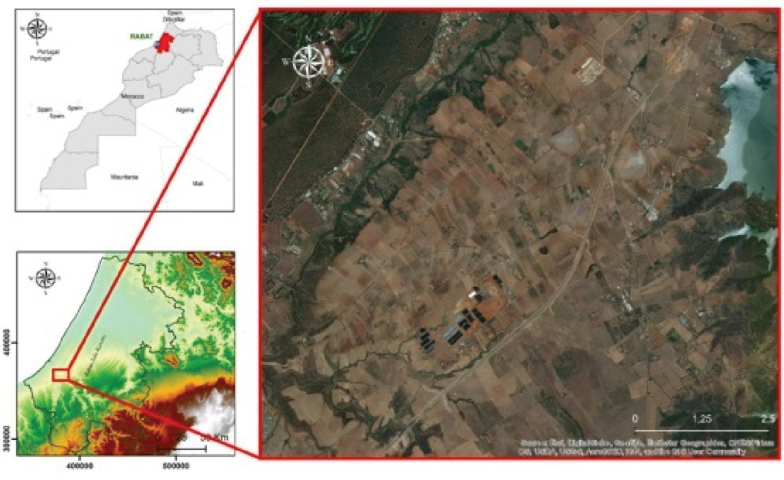

Fig. 1. Oum Azza landfill localization map [27].

Industrial Technologies, France) shown in Fig. 3. This pilot was described in detail in previous papers [31,32]. The pilot is equipped with two modules in series and experiments are performed using RO or NF membranes. The mainly characteristics of those membranes are summarized in Table 2. NF and RO experiments are conducted in two combinations. In combination 1, the performance of single type of NF and RO membrane in the treatment of LFL is studied in continuous mode. In combination 2, NF/RO hybrid system is adopted in which, the permeate of NF membrane (first stage) will feed the RO membrane (second stage). Elazhar et al. [31] used the same configurations to further remove chloride ions in desalination of brackish water, this configuration revealed a clear advantage in reducing the fouling of the RO membrane. After the run, membranes are cleaned with alkaline and acidic cleaning solutions according to the manufacturer's recommendation.

2.2.3. Analytical methods

Samples of the raw and treated LFL are analysed throughout the adopted treatment chain. The main physical and chemical analysis are carried out for several parameters such as COD, TSS, BOD_5, electric conductivity (E), total nitrogen (TN), total phosphorus (TP) and inorganic compounds. All the analyses are done according to standard methods for the examination of water and wastewater [34,35].

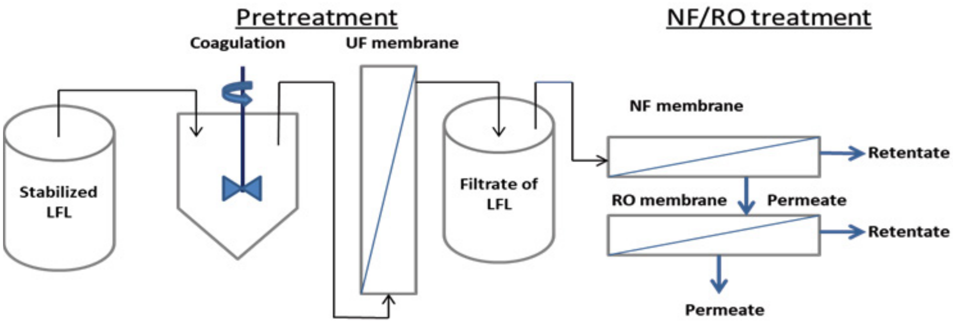

Fig. 2. Schematic diagram of Coag-UF/NF-RO proceeding for LFL treatment.

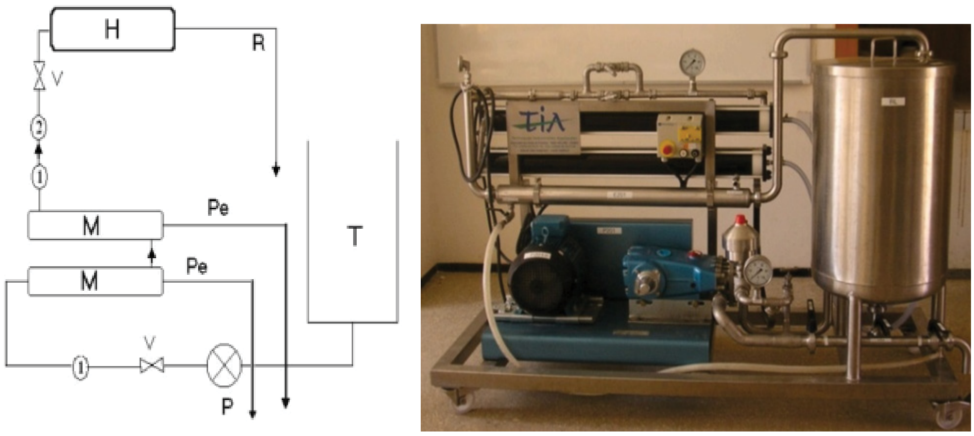

Fig. 3. Schematic diagram and picture of the NF-RO pilot plant. T: Tank; P: Feed pump; V: Pressure regulation valves; M: Membrane module; Pe: Permeate; R: Retentate; H: Heat exchanger; 1: Pressure sensor; 2: Temperature sensor.

Table 2
Characteristics of the used membranes

Membrane	Type	Area (m²)	P_{max} (bar)	pH	Max T (°C)	Materials	Salt rejection (%)	MWCO[a] (Da)
UF	Tubular	–	10	3–11	100	Ceramic	–	–
NF270-4040	Spiral wound	7.6	41	3–10	45	Polyamide	97[b]	200–300
SW TM810	Spiral wound	7	69	1–11	45	Polyamide	99.75[c]	Dense

[a]Molecular weight cut-off is defined as the minimum molecular weight of a solute that is 90% retained by the membrane [33].
[b]Salt rejection based on the following test conditions: 2,000 ppm $MgSO_4$, 25°C and 15% recovery rate at TMP of 4.8 bar.
[c]Salt rejection based on the following test conditions: 32,000 ppm NaCl, 25°C and 8% recovery rate at TMP of 55.2 bar.

3. Results and discussion

3.1. Selection of the ideal coagulant

The coagulation–flocculation process is an important pretreatment to lessen polluting organic matters like COD, TSS, turbidity and colloids in the processing of LFL treatment. Therefore, its effectiveness enhances the efficiency of successive treatment methods by reducing some of organic matter and TSS content [36]. In this study, two coagulants are used, namely $FeCl_3$ and $Al_2(SO_4)_3$ in order to pretreat LFL. Their effectiveness is assessed in terms of COD and TSS removal from LFL at various values of pH and doses of coagulant.

The results show that COD content is crucially reduced after coagulation–flocculation. Type and dose of the used coagulant as well as the pH influence the pretreatment efficiency. Coagulation carried out with ferric chloride (dose in g/L) gives the following maximum COD abatement: 53%, 73% and 62% at pH = 5 (2 g/L), pH = 7(15 g/L) and pH = 8.1 (20 g/L) respectively as shown in Fig. 4. Moreover, the highest reductions of COD achieved with alum are: 60%, 59%, 42% obtained at pH = 8.1 (20 g/L), pH = 7 (15 g/L) and pH = 5 (5 g/L) respectively as shown in Fig. 5. Almost all colloidal particles in LFL are negatively charged in the pH range 5–9 [37] and generally stable and resistant to aggregate due to the electrical repulsion of the surface charge [38]. When coagulant is added, cations resulting from dissolution of coagulant interact with the colloids negatively charged of LFL inducing destabilization and coagulation. Under acidic condition, all organic compounds are fully oxidized to carbon dioxide. However, at the lowest pH, the maximum COD removal is obtained for the lowest dose of coagulants. In addition, the effectiveness of both coagulants is assessed for TSS's reduction. The results obtained are shown in Figs. 6 and 7.

The above results show that a significant TSS's reduction occurred after adding of coagulants $FeCl_3$ and aluminum sulfate $Al_2(SO_4)_3$. This abatement of TSS gradually improved with increasing coagulant doses, because at higher doses more coagulant molecules or ions are available for binding with the suspended solids leading to better reduction. As can be seen in Figs. 6 and 7, the coagulation treatment performed with pH adjustment with low doses ensures a better removal of TSS compared to those carried out without adjustment of the pH (pH = 8.1).

Indeed, the highest TSS reductions are obtained by adding 2 g/L of coagulant $FeCl_3$ and 5 g/L of coagulant $Al_2(SO_4)_3$, which are 84% and 68%, respectively. These results are obtained at optimal value of pH equal to 5. Coagulation with $FeCl_3$ allows a better reduction of COD than with $Al_2(SO_4)_3$.

It is evident that $FeCl_3$ demonstrated the highest treatment efficiency, confirming that ferric chloride is highly effective in the coagulation process as well as one of the most

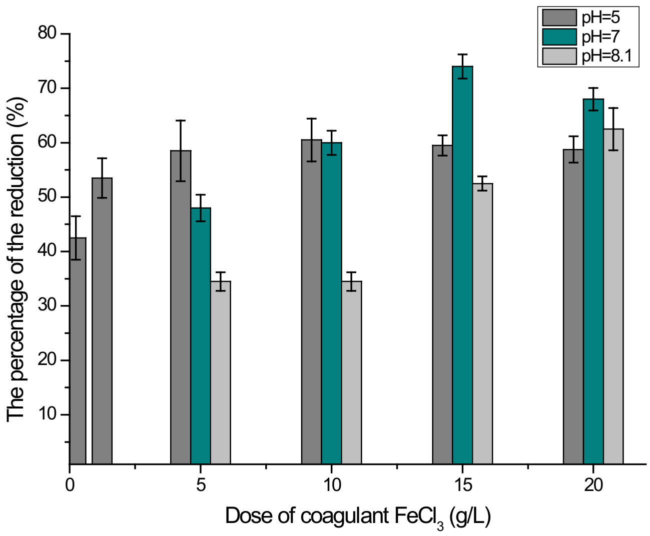

Fig. 4. Effectiveness of the decrease of COD vs. dose of ferric chloride coagulant at different pHs.

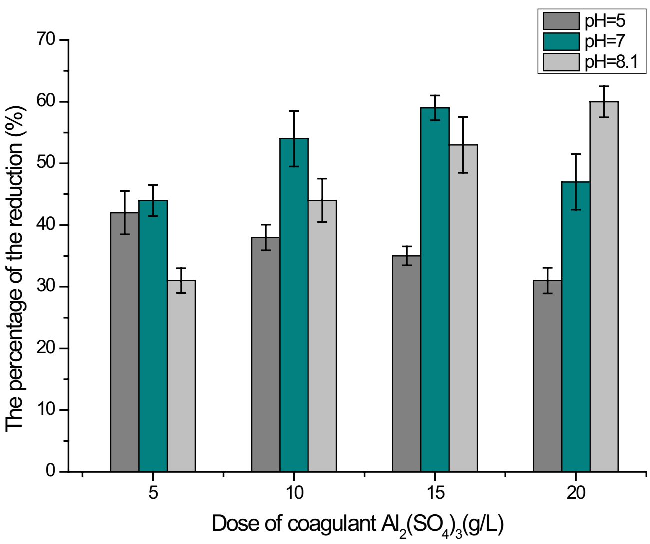

Fig. 5. Effectiveness of the decrease of COD vs. dose of aluminum sulfate coagulant at different pHs.

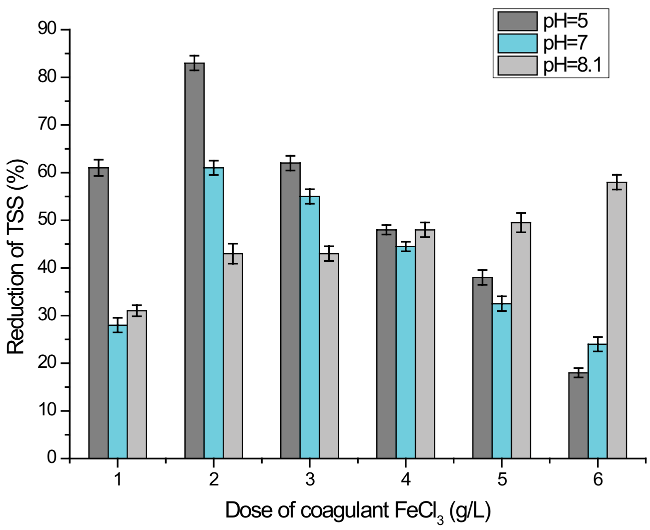

Fig. 6. Reduction of TSS vs. dose of ferric chloride coagulant at different pHs.

promising coagulants. The economic analysis of the operating costs associated with coagulation treatment process has been conducted.

It is important to note that this analysis is just an approximate tool to differentiate the trends in the operating cost associated with the use of coagulation treatment. A suitable economic analysis should consider initial investment, taking into consideration the prices at plant scale, energy, shipping, and storage and labour costs.

Ferric chloride consumption is 2 g/L; it is 2.5 times lower than the values of alum. If it is considered an estimated average price of ferric chloride to be around 3.2 and 2.8 US $/kg of aluminum sulfate. By comparing the cost of reagent per treated leachate volume (US$/m^3), values of 0.64 and 1.4 US $/m^3 are obtained for ferric chloride and alum respectively. This is 2 times in favor of ferric chloride, being acceptable for the treatment. Thus, due to its low cost, ferric chloride is probably an interesting coagulant for LFL pretreatment.

The pretreated LFL will then be subjected to a UF membrane separation treatment to remove persistent pollutants and improve the quality of the treated LFL.

3.2. Combination Coag-UF

In this part, coagulation and UF are combined according to the hybrid configuration coagulation-UF (Coag-UF) for LFL treatment. The UF experiment is performed at TMP of 6 bar corresponding to a flux of 116 L/h/m^2. The results obtained of effectiveness of removal of COD, TSS and Fe as well as the decrease of electric conductivity (E) are depicted on Fig. 8.

The analysis of the result shows that the LFL treatment by only coagulation using $FeCl_3$ allows the removal of 53% of COD, 84% of TSS, and 50% of Fe. Consequently, the electric conductivity of the coagulated effluent increases up to 28%. Indeed, in an acid medium, $FeCl_3$ coagulant could be transformed into polynuclear's form like $Fe(OH)_3$ and $Fe(OH)_2$. Reactions by ferric cations in LFL samples are greatly influenced by presence of humic substances, which represent approximately 75% of stabilized LFL, they precipitate and promote reduction of Fe. However, for a single and direct treatment of UF of raw LFL, the removal of COD is close to 45%, while the retention of TDS, as revealed by measurement of electric conductivity, is rather weak (11%) compared to of 70% of organic pollution as TSS [39]. As expected, due to their structure, UF membrane cannot reduce salinity of effluent. Comparatively to other two treatments, single UF and single Coag, the results show that the integrated Coag-UF combination allows a significant reduction of LFL contaminants: 62% for COD, 89% for TSS and 62% for Fe. On the other hand, electric conductivity remains high. Hence, the flocs created by coagulation will be more easily retained by UF membrane at low operating TMP.

3.3. Combination Coag-UF/NF/RO

As developed in the section 3.2, due to the complexity and variance of the LFL as well as to their high TDS, the integrated Coag-UF method failed to reject TDS and the remaining pollutants. Hybrid process including, NF and RO membranes in combination with Coag-UF have the ability to retain TDS and the remaining pollutants, especially for treated water from LFL to meet salinity standards that coagulation alone or combined with ultrafiltration fail to meet. For this purpose, three hybrid configurations are investigated: Coag-UF/NF, Coag-UF/RO and Coag-UF/NF/RO. The applied TMP is 40 bar for NF corresponding to 52.37 L/h/m^2 and 45 bar for RO corresponding to 43.59 L/h/m^2 and 32 bar for NF/RO corresponding to 64.89 L/h/m^2 of water flux. Fig. 9 shows the effectiveness of the decrease of various pollution indicators from LFL using the three hybrid configurations.

Among the three hybrid configurations for the treatment of LFL initially treated by Coag-UF process, the best removal efficiencies are exhibited by Coag-UF/RO and Coag-UF/NF/RO hybrid system. The high reductions of COD, E and TSS (>90%) are obtained by Coag-UF/RO and Coag-UF/NF/RO configurations. Meanwhile, the nitrite, nitrate and sulphate anions rejection reach more than 78% in most cases for two hybrid systems Coag-UF/NF/RO and Coag-UF/RO.

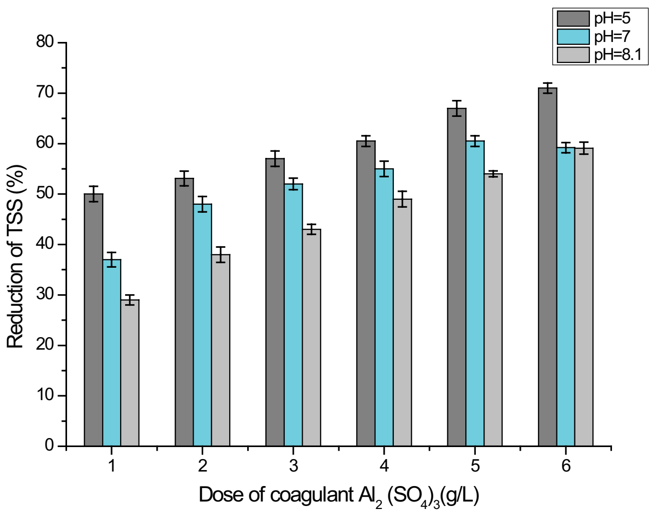

Fig. 7. Reduction of TSS vs. dose of aluminum sulfate coagulant at different pHs.

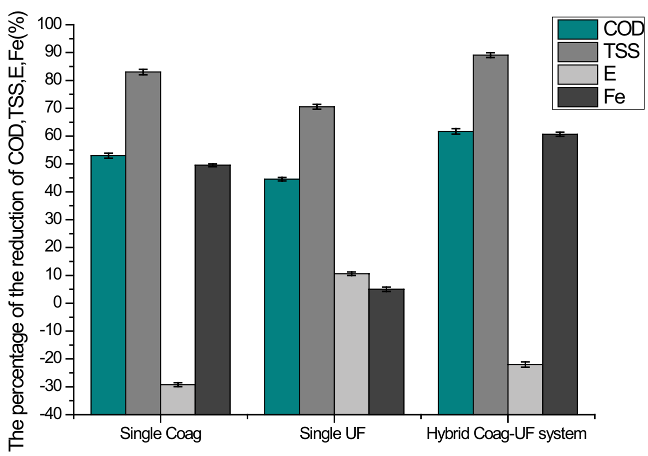

Fig. 8. Effectiveness of removal of COD, TSS, E and Fe from LFL by coagulation, UF and Coag-UF.

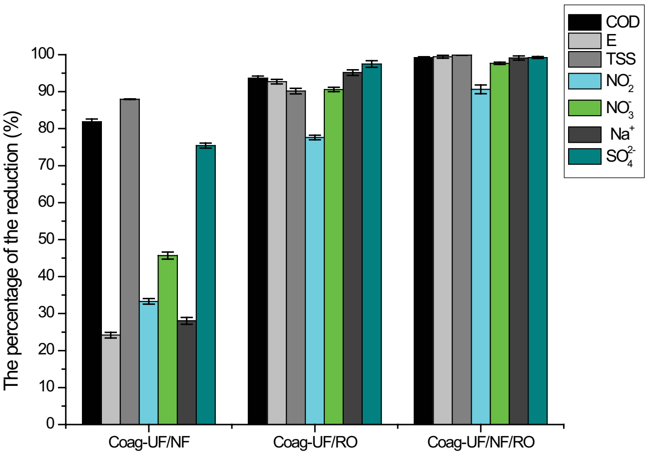

Fig. 9. Effectiveness of the decrease of several parameters from LFL using the three hybrid configurations.

Compared to the above combinations, rejection of TDS reaches 24%, while anions are moderately rejected by Coag-UF/NF combination except sulphate which is rejected up to 75.9%.This difference could be explained by the nature of NF membrane, which cannot completely retain all organic compounds, a small fraction of this organic matter passes through the membrane pores thus reducing the retention of these compounds. Moreover, NF membranes have propensity to retaining divalent ions preferentially than monovalent ones.

In terms of permeate quality; it appears that the Coag-UF/NF hybrid system is not able to fulfill the recommended discharge water since the levels of electric conductivity exceed the recommended standards (2,700 µS/cm). An additional treatment is required. However, the water quality in terms of TDS is improved by the two others hybrids systems Coag-UF/NF/RO and Coag-UF/RO for which electric conductivity value reaches 315 and 2,516 µS/cm respectively. The integrated systems can be ranked in the following order: Coag-UF/NF/RO > Coag-UF/RO > Coag-UF/NF. The combined NF/RO system as downstream of the Coag-UF pretreatment significantly improves the permeate quality. The main advantage of NF over RO is the possibility to operate under lower TMP and higher recoveries. NF is defined as a process with characteristics between RO and UF and with different retention efficiencies for either mono or multivalent ions. Thus, its placement upstream RO membrane could reduce precipitation and scaling potential and inducing to lessen driven TMP of RO process in the following stage. However, single RO as downstream to Coag-UF system is hampered by fouling caused by substantial organic compounds and on the other hand by scaling phenomenon due to the high TDS of LFL. The benefit of integration NF-RO in the treatment chain of LFL involves minimizing scaling propensity of feed water, lowering operating TMP and energy requirement and finally increasing the quantity and the quality of the permeate. Moreover, knowing that the public cost of electricity in Morocco is close to US $ 0.1/kWh [40,41], the calculation of the overall water recovery rate and energy consumption values for the three hybrid process combinations: Coag-UF/NF, Coag-UF/RO and Coag-UF/NF/RO is based on the expressions.

Overall water recovery rate (Y_T):

$$Y_T = \frac{Y_{\mathrm{NF}}}{1 - Y_{\mathrm{RO}}\left(1 - Y_{\mathrm{NF}}\right)} \quad (1)$$

where Y_{NF} and Y_{RO} are the recovery rate (%) in each stage, respectively.

Specific energy consumption (SEC) for two stages [42]:

$$\mathrm{SEC} = \frac{\left(P_{\mathrm{RO}} + P_{\mathrm{NF}}\right) \times 100}{36 \times Y \times \eta} \quad (2)$$

where P_{RO}, P_{NF}, η and Y are the applied pressure in RO and NF stage (bar), the global pumping system efficiency and the overall recovery rate (%), respectively.

In terms of recovery rate and energy consumption, it appears that the Coag-UF/NF/RO hybrid system is more technically attractive thanks to its remarkable improvement over the two others combinations. As a matter of fact, on the basis of the above analysis, it can be concluded that the energy consumption can be reduced by increasing the number of stages. It should also be noted that the cost of energy decreases. It can be ranked in the following order: Coag-UF/NF/RO < Coag-UF/NF < Coag-UF/RO, while the water recovery rate increases in the same order. Coag-UF/NF hybrid system works with 42.2% of recovery rate and produces 3,025.23 L/h of permeate flow which is more than the feed processed by only RO unit. Furthermore, the recovery is well improved up to 57.2% corresponding to 3,452.47 L/h of permeate flux when NF is positioned upstream in the first stage of RO process for Coag-UF/NF/RO hybrid system. Table 3 describes the energy consumption, energy cost estimates and performances comparison of three hybrid process combinations: Coag-UF/NF, Coag-UF/RO and Coag-UF/NF/RO in treatment of stabilized LFL.

4. Conclusion

Legal compliance of reuse of stabilized LFL and its discharge into environment has been successfully accomplished, using Coag-UF/NF/RO chain's process. The investigation of the raw LFL characteristics has illustrated that it contains high concentrations of indicators pollutants and salinity. Firstly, a comparative assessment of the two coagulants of $FeCl_3$ and $Al_2(SO_4)_3$ was performed for the remediation of LFL. The ferric chloride coagulant was chosen for its low cost as 0.64 US$/m^3 per volume of treated LFL volume and its performances to lessen the load of impurities such as COD and TSS on the subsequent membrane separation step, by reducing 53% of COD and 84% of TSS from raw LFL. Afterwards, $FeCl_3$ was integrated into Coag-UF combination method. A hybrid process of Coag-UF, such as pretreatment step of LFL led to high removal rates of COD, TSS and iron. On the contrary, The Coag-UF combining system has failed to reach the required standards in terms of TDS and electrical conductivity (E). For these reasons, NF and RO membranes are combined to Coag-UF in order to complete and enhance

Table 3
Performances and energy comparison of three hybrid systems: Coag-UF/NF, Coag-UF/RO and Coag-UF/NF/RO

	Coag-UF/NF	Coag-UF/RO	Coag-UF/NF/RO
E_{Feed} (µS/cm)	31,500		
TMP (bar)	40	45	32
Flux (L/h)	3,025.23	2,154.58	3,452.47
Recovery rate (%)	42.2	35.1	57.2
$E_{Permeate}$ (µS/cm)	23,900	2,520	315
$E_{Concentrate}$ (µS/cm)	37,056	47,207	73,262
Salinity rejection (%)	24	92	99
Energy consumption (kWh/m^3)	0.032	0.044	0.0194
Energy cost (US $/m^3)	0.0032	0.0044	0.00194

the efficiency treatment of LFL. Based on performances' comparison of Coag-UF/NF/RO systems and taking into account the permeate quality, the integrated systems can be ranked in the following order: Coag-UF/NF/RO > Coag-UF/RO > Coag-UF/NF. The Coag-UF/NF/RO hybrid system increased the water recovery rate of LFL by up to 57.2%, leading to a net reduction in the quantity of brine. In addition, the retention of TDS reached 99% and the quality of the permeate was significantly improved when the NF is placed upstream of RO. Moreover, the Coag-UF/NF/RO and Coag-UF/RO hybrid systems were able to produce quality water according to Directive FAO and Water Reuse standard for Irrigation, Land Watering, Morocco. Lastly, because the Coag-UF/NF/RO hybrid system allowed the best performances in LFL treatment and consumes less energy than the others combined systems, it was selected as the best solution for treating stabilized landfill leachate. At the same time, this hybrid system can minimize the fraction of brine disposal dumping to sewage, making it environmentally friendly. Thus, integrated systems can be employed to treat leachate with high efficiency and low energy expense.

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