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POTENTIAL RESOURCES RECOVERY OPPORTUNITIES FROM WASTEWATER: A REVIEW

CƠ HỘI TIỀM NĂNG ĐỂ THU HỒI NGUỒN TÀI NGUYÊN TỪ NƯỚC THẢI

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ABSTRACT

Nowadays, two important issues to achieve sustainable development which need to be urgently considered are water scarcity and natural resource depletion. According to UN 2006, around 700 million people in 43 countries suffer today from water scarcity. Besides, due to the population growth, natural non-renewable resources are forecasted to be depleted in the coming years. Therefore, wastewater is now recognized not only as a needed treated resource but also as a "renewable" resource, in which valuable components can be recovered. A number of technologies have been recently investigated to achieve the objective of valuable resources recovery from wastewater in order to reduce water scarcity, resource depletion, preserve the environment and reduce the cost of wastewater treatment. This paper reviews treatment methods for water reclamation, acid/base regeneration from wastewater and phosphorous recovery from municipal wastewater to achieve sustainable development. The treatment options are discussed and novel treatment processes are proposed based on a literature review.

Keywords**:** *Water reclamation; phosphate recovery; acid/base regeneration, wastewater; renewable resource.*

TÓM TẮT

Ngày nay, hai vấn đề quan trọng để đạt được sự phát triển bền vững cần được xem xét là tình trạng khan hiếm nước và cạn kiệt tài nguyên thiên nhiên. Theo UN 2006, khoảng 700 triệu người tại 43 quốc gia bị ảnh hưởng bởi tình trạng khan hiếm nước. Bên cạnh đó, cùng với việc tăng dân số, các nguồn tài nguyên thiên nhiên không tái tạo được dự báo sẽ cạn kiệt trong những năm tới. Do đó, nước thải hiện nay không chỉ được coi là nguồn nước cần xử lý mà còn là một nguồn tài nguyên có khả năng thu hồi được. Một số công nghệ gần đây đã được nghiên cứu để đạt được mục tiêu thu hồi tài nguyên có giá trị từ nước thải nhằm giảm sự khan hiếm nước, cạn kiệt tài nguyên, bảo vệ môi trường và giảm chi phí xử lý nước thải. Nghiên cứu này xem xét các phương pháp xử lý để tái sử dụng nước, tái tạo axit / bazơ từ nước thải và thu hồi phốt pho từ nước thải đô thị để đạt được phát triển bền vững. Các phương pháp xử lý được thảo luận và từ đó đề ra phương pháp mới dựa trên việc xem xét tổng quan.

Từ khóa: *Tái sử dụng nước; thu hồi photphate, tái tạo axit/bazo; nước thải; tài nguyên có khả năng tái tạo.*

1. INTRODUCTION

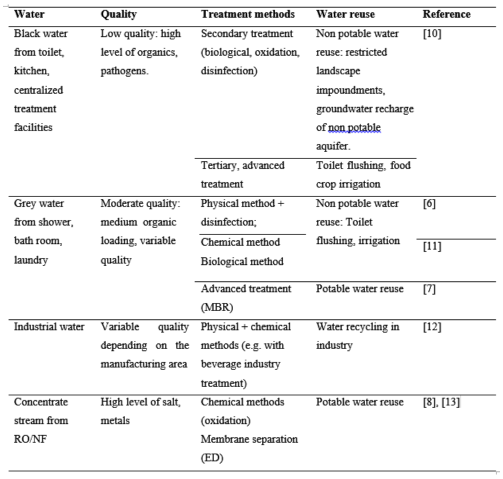
Due to the global warming and population growth, many parts in the world are now facing a water crisis and depletion of natural resources. The world population is at around 7.2 billion in 2013 and will reach 8.1 billion in 2025 [1], therefore, the volume of water and the amount of resources need to be increased to meet the demand. This leads to the opinion of one-time using water should be changed in many water stressed regions [2]. In the past, the goal of the wastewater treatment plant is to protect the environment and public health. However, wastewater is now recognized not only as a needed treated resource but also as a "renewable" resource to recover valuable components [3]. These components such as water, noble metals, regenerated acid, base from corresponding salt in industrial wastewater, nutrients (phosphorus, nitrogen), and energy can be recovered from domestic wastewater, industrial wastewater and concentrated streams from reverse osmosis and nanofiltration. By utilizing this recovery approach, not only the maximal benefits for resources availability and quality can be achieved but also the negative impact of wastewater on the environment is reduced [3].

This review aim to provide (i) an overview of water reclamation, (ii) description of acid/base regeneration from wastewater, (iii) phosphate recovery and (iv) proposals for treatment options based on literature reviews.

2. WATER RECLAMATION

Many water reclamation and reuse plants are built in water stressed areas such as Belgium, Singapore, United States, Australia, Mexico, and others (Levine and Asano, 2004). NEWater in Singapore is also using an advanced system consisting of a dual membrane microfiltration/reverse osmosis and UV technology to reuse the brine of an RO system. to increase RO recovery up to 95% [4]. In the United States, the Oregon County Water District has been using reclaimed water for California's indirect potable water supply by recharging into ground water since 1962 [5].

Table 1. *Summary of water quality and treatment methods for water reuse*



Water	Quality	Treatment methods	Water reuse	Reference
Black water from toilet, kitchen, centralized treatment facilities	Low quality: high level of organics, pathogens.	Secondary treatment (biological, oxidation, disinfection)	Non potable water reuse: restricted landscape impoundments, groundwater recharge of non potable aquifer.	[10]
		Tertiary, advanced treatment	Toilet flushing, food crop irrigation	
Grey water from shower, bath room, laundry	Moderate quality: medium organic loading, variable quality	Physical method + disinfection;	Non potable water reuse: Toilet flushing, irrigation	[6]
		Chemical method Biological method		[11]
		Advanced treatment (MBR)	Potable water reuse	[7]
Industrial water	Variable quality depending on the manufacturing area	Physical + chemical methods (e.g. with beverage industry treatment)	Water recycling in industry	[12]
Concentrate stream from RO/NF	High level of salt, metals	Chemical methods (oxidation) Membrane separation (ED)	Potable water reuse	[8], [13]

Wastewater reclamation can be used for either non-potable or potable applications. Non-potable reuse systems have lower requirements than potable systems. The typical technologies for water treatment and reuse for non-potable purpose often include physical, chemical and biological systems. March et al., 2004 [6] reported that wastewater from a hotel after treatment by nylon sock type filters, sedimentation and disinfection could be used for toilet flushing. Li et al., 2008 [7] used a submerged spiral wound ultrafiltration module for non-potable reuse. A high efficiency (83.4%) of total organic carbon (TOC) removal could be achieved. Besides, 95% DOC removal was observed within 6 h by applying $FeCl_3$ coagulation and photocatalysis (UVC/TiO_2) [8]. Moreover, Gross et al., 2007 [9] also developed environmentally friendly method to reuse wastewater for landscape irrigation purposes. The system was denoted as a 'recycled vertical flow constructed wetland', in which a vertical flow constructed wetland and water recycling were combined. The system had a good efficiency of removing all the suspended solids and BOD, and about 80% of COD after 8h, but not all fecal coliforms. Although black water is very dirty with lots of contaminants, it was also considered as a non-potable water reuse after being treated [10]. Pidou et al. in [11] applied coagulation and a magnetic ion exchange resin to treat shower wastewater. The removal efficiencies were 63.7% for chemical oxygen demand (COD), 88.8% for biological oxygen demand (BOD), 90.8% for turbidity, 12.8% for total nitrogen and 94.6% for phosphate by coagulation with aluminum salt at the optimal conditions. Besides domestic wastewater, industrial wastewater was also studied by applying physical and chemical method for water recycling in that industry, i.e beverage [12]. Recently, due to the increasing demand of water reclamation for potable reuse, reverse osmosis (RO) and nanofiltration (NF) are more and more used. However, large volumes of RO concentrates containing high salt concentrations along with calcium, magnesium and organic matter are discharged to the environment. Zhang et al in [13] used electrodialysis to separate ion from wastewater into dilluate and concentrate stream and used dilluate stream as product water for recycling. Water reuse can also be achieved from the brine of these membrane technologies for increasing the recovery of membrane systems and to reduce the impact of pollution.

3. ACID/ BASE REGENERATION

It is well known that a waste stream such as the pickling liquor from metal manufacturing contains high concentrations of acids and metals such as Fe, Cu, Ni, and is considered hazardous. Various methods such as pyrohydrolysis, solvent extraction, ion exchange and membrane separation can be used to recover inorganic acid from this waste and prevent environmental pollution when discharged [14].

In a fluidized bed for acid regeneration by pyrohydrolysis process, hydrochloric acid and iron oxide are converted from spent liquor in the presence of water vapor and oxygen at 850^{o}C:4 $FeCl_2$ + 4 H_2O + O_2 → 8 HCl + 2 Fe_2O_3 [15]. Additionally, regeneration of spent HCl acid can be also obtained in a spray roasting reactor at a lower temperature (450^{o}C). With the heat, $MgCl_2.6H_2O$ reacts with water vapor to become MgO and HCl following the equation: $MgCl_2 + H_2O \rightarrow MgO + 2\ HCl$ [16]. However, it is expensive to apply pyrohydrolysis to regenerate acid due to the high energy consumption.

Many studies were also carried out to investigate the recovery of acid from waste solutions by solvent extraction. This technology is suitably used when the waste solutions have high concentrations of contaminants and for large scale operation [14]. Agrawal et al., 2008 [17] used tris-2-ethylhexylamine (TEHA) to extract acid from zinc bleed stream. An increase in solvent concentration led to an increase in extraction capacity of H_2SO_4. Recovery/removal of hydrochloric acid from leach liquor using solvent extraction method was also studied by Sarangi et al. [18], in which Alamine 336 (tri-octyl/decyl amine), Aliquat 336 ($(R_3NCH_3)^+Cl^-$, R = octyl/decyl), TBP (Tri-n-butyl phosphate) and Cyanex 923 were extractants. The acid from the loaded organics of these extractants was easily stripped with water, except for Aliquat 336. Solvent extraction can be an effective method to recover acid from waste streams; however, there are also some impurities such as heavy metals in the product due to the co-extraction; with 75% of TEHA concentration, about 1-2% of zinc was extracted [17].

Besides the acid recovery from the acid waste, acid and base also can be generated from salty wastewater. A treatment process with bipolar membrane electrodialysis (EDBM) not only removes the salt from the wastewater to control pollution but also produces acid/base from the corresponding salt. Acid and base recovery from wastewater by electrodialysis with bipolar membranes is one of the most promising applications to control water pollution and to achieve sustainable development [19]. EDBM with a two compartment cell (bipolar membrane/cation exchange membrane) was studied by Lameloise and Lewandowski, 2012 [20] to recover L-malic acid from a by-product of alcohol fermentation containing mainly sugars, alcohols, minerals, malate and other organic salts with a current efficiency of 87-97%. The L-malic acid recovery was 93–97% and the energy consumption was 1.15–1.27 kWh/kg L-malic acid. Yang et al., 2014 [21] also used EDBM to regenerate 1 M mixed acid and base from RO concentrate generated in a seawater desalination system at a current density of 57 mA/cm^2, flow rate of 0.3 L/h and effective membrane area of 88 cm^2. The recovery efficiency for acid and base from these studies was high and the energy consumption of EDBM was low, which proves that EDBM is feasible to regenerate acid and base from wastewater. However, if the feed solution is diluted, the energy consumption is high and therefore, it is not economical to apply EDBM. Moreover, membrane fouling is one of the difficulties to recover acid and base due to hydroxide precipitation from the base stream of multivalent metal ions such as Ca^{2+}, Mg^{2+}, Zn^{2+}, Cu^{2+}, Pb^{2+}, Ni^{2+}, Al^{3+}, Fe^{3+}, and Cr^{6+} on the ionic membrane [19].

4. PHOSPHATE RECOVERY

Phosphorus (P) is an essential and limited element, therefore phosphate recovery from wastewater is to be considered an important aspect in sustainable development [22]. The most developed technique that can be applied to recover phosphate is precipitation/crystallization as struvite and calcium phosphate [23-25]. Calcium phosphate can be directly used in the phosphoric acid and fertilizer production. Struvite can be formed by addition of ammonia and magnesium to phosphate to obtain a precipitate of magnesium ammonium phosphate ($MgNH_4PO_4$) and has a slow release mechanism.

However, this precipitation technology still has drawbacks since low feed concentrations lead to low supersaturation levels, and a low efficiency. The minimum P concentration required for good precipitation is 50 mgP/L at neutral pH [26], while the concentration of phosphate in municipal wastewater is low (from 18.5 to 48.3 mgP/L[27]. Consequently, to achieve a high recovery efficiency, new techniques are to be developed in order to concentrate phosphate prior to the precipitation process.

Biological treatment [28], adsorption [29-30], ion exchange [31-32] and nanofiltration [33-34] are common methods to concentrate and recover phosphate from wastewater. One of the most promising technologies to overcome these constraints is electrodialysis, a non-pressure driven membrane process in which ion exchange membranes are arranged under an electrical field [35]. It is used for desalination, concentration of ions from a solution [36], and production/recovery of acid and base from corresponding salts with bipolar membranes [19], [37-38]. Recently, electromembrane processes have been studied to recover phosphate from nanofiltration concentrate by using an electrophoretic system with one cation exchange membrane between a cathode and an anode. The increase in pH at the cathode due to the reaction: $4\ H_2O + 4\ e^- \rightarrow 4\ OH^- + 2\ H_2$ causes a shift from $H_2PO_4^-$ ions to mainly HPO_4^{2-} or PO_4^{3-} ions, which led to higher supersaturation and therefore precipitation of calcium phosphate occurred [39]. In another application, phosphate from anaerobic potato processing wastewater was recovered as struvite by a selectrodialysis and a struvite reactor [40]. These examples prove that electro-membrane processes are feasible to recover phosphate from wastewater; however, optimized operation parameters such as pH, initial concentration or current density and other effects of competing ions in the wastewater should be further determined.

5. PROPOSAL FOR RECOVERY

Although water reclamation, acid/base regeneration and phosphorus recovery have been already studied, the technologies still remain some difficulties such as scaling on the membrane, and low phosphate concentration leading low precipitation efficiency.

With water reclamation and acid/base regeneration, it is necessary to have a pretreatment method to reduce the scaling potential such as the precipitation of metal on the ionic membranes surface in electrodialysis and bipolar membrane electrodialysis. In view of phosphate recovery, higher phosphate concentrationis needed to obtain calcium phosphate precipitation.

To precipitate hardness and metal which is scaling potential, conventional precipitation and ion exchange are normally used. However, they have some drawbacks such as sludge production, longer contact time, complicated system and expensive. The fluidized pellet reactor can overcome the difficulties of the conventional precipitation method and of ion exchange resins. It has been proven to be efficient in removing hardness (calcium and magnesium) from water for drinking water [41], phosphate recovery [42], fluoride and metal removal [43-44]. This is a cylindrical reactor with a height ranging from 5 to 10 m and a diameter of 1.5 to 3 m, containing seeding material, which is usually garnet sand with diameter from 0.2 to 0.6 mm. The water is pumped through nozzles at the bottom and upwards in the reactor at the superficial velocity varying between 80 to 100 m/h so that the pellet can be fluidized [45]. In this zone, the water is mixed with a caustic reagent (NaOH or $Ca(OH)_2$). After crystallization on the surface, the pellets become heavier (to a maximum pellet diameter of 1 mm), then sink to the bottom of the reactor, from where they are regularly discharged and replaced by fresh seed material.

Besides that, to increase the phosphate concentration, Selectrodialysis is a novel electrodialysis system in which a monovalent selective anion exchange membrane (MVA) is set between cation exchange membrane (CM) and anion exchange membrane (AM) to fractionate multivalent anions from the solution, dividing the stack into three kinds of compartments: feed, product and brine [13]. Due to the applied electrical field, the anions (chloride, nitrate, sulphate, carbonate and phosphate) move across anion exchange membranes while the cations (sodium, potassium, calcium and magnesium) move across cation exchange membranes. Since monovalent selective anion exchange membranes are set between anion and cation exchange membrane, the multivalent ions such as sulphate, carbonate and phosphate are kept in the product compartment (Fig. 1). The objective of selectrodialysis application is to concentrate divalent anions while to reduce the monovalent ions in the product compartment based on the integration of a monovalent selective anion exchange membrane.

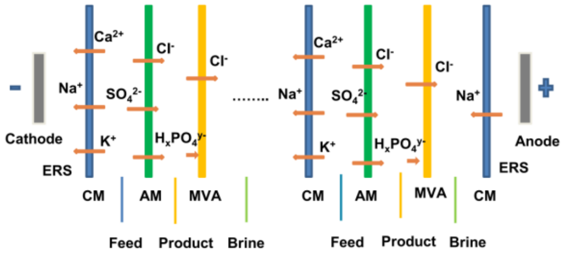


Fig. 1. *Schematic diagram of a selectrodialysis stack*

From the aforementioned things, the novel technology by applying the pellet reactor and selectrodialysis as pretreatment method is proposed to obtain the resource recovery from wastewater.

6. CONCLUSION

Extracting resources from wastewater has become essential for sustainable development. Several researchers have already investigated current options. To meet the environmental aspect in sustainability, the wastewater should be considered as a renewable resource for water, nutrients and other materials in the future. The integrated system comprising conventional methods (physical, chemical and biological methods) and advanced methods (MBR, EDBM…) was technically feasible in recovering resources from wastewater, reducing water pollution, preventing eutrophication and yielding valuable and sustainable products.

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REFERENCES

[1] United Nations, Department of Economic and Social Affairs, Population Division, 2013. World Population Prospects: The 2012 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.227.

[2] Levine, A. D., Asano, T., 2004. Recovering sustainable water from wastewater. Environ.Sci. Tech. June 1, 2004 201A - 2008 A.

[3] Guest, J.S., Skerlos, S.J., Barnard, J.L., Bruce Beck, M., Daigger, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., Macpherson, L., Mihelcic, J.R., Pramanik, A., Raskin, L., Van Loosdrecht, M.C.M., Yeh, D. and Love, N.G. ,2009. A New Planning and Design Paradigm to Achieve Sustainable Resource Recovery from Wastewater1. Environ. Sci. Technol. 43(16), 6126-6130.

[4] Kazner, C., Wintgens, T., Dillon, P., 2012. Water Reclamation Technologies for Safe Managed Aquifer Recharge. IWA Publishing, London, UK.

[5] National Research Council, 1998. Issues in Potable Reuse: The viability of Augmenting Drinking Water Supplies with Reclaimed Water. National Academy Press: Washington, DC.

[6] March, J.G., Gual, M., Orozco, F., 2004. Experiences on greywater re-use for toilet flushing in a hotel (Mallorca Island, Spain). Desalination 164, 241–247.

[7] Li, F., Behrendt, J., Wichmann, K., Otterpohl, R., 2008. Resources and nutrients oriented greywater treatment for non-potable reuses. Water Sci. Technol. 57, 1901–1907

[8] Zhou T., Lim T., Chin S., Fane A.G., 2011. Treatment of organics in reverse osmosis concentrate from a municipal wastewater reclamation plant: Feasibility test of advanced oxidation processes with/without pretreatment. Chem. Eng. J. 166, 932–939.

[9] Gross, A., Shmueli, O., Ronen, Z., Raveh, E., 2007. Recycled vertical flow constructed wetland (RVFCW) - a novel method of recycling greywater for irrigation in small communities. Chemosphere 66, 916–23

[10] US EPA Office of Technology Transfer and Regulatory Support. 1992. Guidelines for Water Reuse. EPA/625/R-92/004. September 1992.

[11] Pidou, M., Avery, L., Stephenson, T., Jeffrey, P., Parsons, S.A., Liu, S., Memon, F.A., Bruce Jefferson, B., 2008. Chemical solutions for greywater recycling. Chemosphere 71, 147–155.

[12] Hussain, R., Sattar, S., Khan, M. H., Nafees, M., 2013. Low Cost Wastewater Treatment at Beverage Industry, Hattar Industrial Estate, Pakistan - A Case Study. Int. J. Environ. Prot. 3, 23 – 28.

[13] Zhang, Y., Van der Bruggen, B., Pinoy, L., Meesschaert, B., 2009. Separation of nutrient ions and organic compounds from salts in RO concentrates by standard and monovalent selective ion-exchange membranes used in electrodialysis. J. Membr. Sci. 332, 104 - 112.

[14] Agrawal, A., Sahu, K.K., 2009. An overview of the recovery of acid from spent acidic solutions from steel and electroplating industries, J. Hazard.Mater. 171, 61 - 75.

[15] European Commision, 2001. Report for Integrated Pollution Prevention and Control (IPPC), Reference Document on Best Available Techniques in the Ferrous Metals Processing Industry. http://eippcb.jrc.ec.europa.eu/reference/BREF/fmp_bref_1201.pdf.

[16] Harris, L.J.F., 1994. Introduction to spray roasting process for hydrochloric acid regeneration and its application to mineral processing. Hydrometallurgy, Cambridge, Chapman & Hall, London, 923–937.

[17] Agrawal, A., Kumari, S., Sahu, K.K., 2008. Liquid- liquid extraction of sulphuric acid from zinc bleed stream. Hydrometallurgy 92, 42 – 47.

[18] Sarangi, K., Padhan, E., Sarma, P.V.R.B., Park, K.H., Das, R.P., 2006. Removal/recovery of hydrochloric acid using Alamine 336, Aliquat 336, TBP, and Cyanex 923. Hydrometallurgy 84, 125 – 129.

[19] Huang, C.H. and Xu, T., 2006. Electrodialysis with Bipolar Membranes for Sustainable Development. Environ. Sci. Technol. 40, 5233 - 5243.

[20] Lameloise, M.L., Lewandowski, R., 2012. Recovering L-malic acid from a beverage industry waste water: Experimental study of the conversion stage using bipolar membrane electrodialysis, J. Membr. Sci. 403 - 404, 196 -202.

[21] Yang, Y. , Gao, X., Fang, A., Fu, L., Gao, C., 2014. An innovative beneficial reuse of seawater concentrate using bipolar membrane electrodialysis, J. Membr. Sci. 449, 119 - 126.

[22] Cordell, D., Rosemarin, A., Schröder, J.J. and Smit, A.L., 2011. Towards global phosphorus security: A systems framework for phosphorus recovery and reuse options. Chemosphere 84, 747 - 758.

[23] Warmadewanthi and Liu, J.C., 2009. Recovery of phosphate and ammonium as struvite from semiconductor wastewater. Sep. Purif. Technol. 64, 368 - 373.

[24] Okano, K., Uemoto, M., Kagami, J., Miura, K., Aketo, T., Toda, M., Honda, K. and Ohtake, H., 2013. Novel technique for phosphorus recovery from aqueous solutions using amorphous calcium silicate hydrates (A-CSHs). Water Res. 47, 2251 - 2259.

[25] Korchef, A., Saidou, H., Amor, M.B., 2011. Phosphate recovery through struvite precipitation by CO2 removal: Effect of magnesium, phosphate and ammonium concentrations. J. Hazard.Mater. 186, 602 - 613.

[26] Carlsson, H., Aspegren, H., Lee, N. and Hilmer, A., 1997. Calcium phosphate precipitation in biological phosphorus removal systems. Water Res. 31, 1047 - 1055.

[27] Korsak, L., Moreno, L., 2006. Water Pollution VIII: Modelling, Monitoring and Management, WIT Press, Southampton, UK.

[28] Kodera, H., Hatamoto, M., Abe, K., Kindaichi, T., Ozaki, N., Ohashi, A., 2013. Phosphate recovery as concentrated solution from treated wastewater by a PAO-enriched biofilm reactor. Water Res. 47, 2025 - 2032.

[29] Xiong, W., Peng, J., 2008. Development and characterization of ferrihydrite-modified diatomite as a phosphorus adsorbent. Water Res. 42, 4869 - 4877.

[30] Wahab, M.A., Hassine, R.B., Jellali, S., 2011. Posidonia oceanica (L.) fibers as a potential low-cost adsorbent for the removal and recovery of orthophosphate. J. Hazard.Mater. 191, 333 - 341.

[31] Kumar, M., Badruzzaman, M., Adham, S. and Oppenheimer, J., 2007. Beneficial phosphate recovery from reverse osmosis (RO) concentrate of an integrated membrane system using polymeric ligand exchanger (PLE). Water Res. 41, 2211 - 2219.

[32] Wu, R.S.S., Lam, K.H., Lee, J.M.N. and Lau, T.C., 2007. Removal of phosphate from water by a highly selective La(III)-chelex resin. Chemosphere 69, 289 - 294.

[33] Disha, V.J., Aravindakumar, C.T. and Aravind, U.K., 2012. Phosphate Recovery by High Flux Low Pressure Multilayer Membranes. Langmuir 28, 12744 - 12752.

[34] Hong, S.U., Ouyang, L. and Bruening, M.L., 2009. Recovery of phosphate using multilayer polyelectrolyte nanofiltration membranes. J. Membr. Sci. 327, 2 - 5.

[35] Tanaka, Y., 2007. Ion Exchange Membrane: Fundamentals and Applications, Elsevier, Amstedam.

[36] Xu, T., Huang, C., 2008. Electrodialysis-Based Separation Technologies: A Critical Review. AlChE J. 54(12), 3147 - 3159.

[37] Pourcelly, G., 2002. Electrodialysis with Bipolar Membranes: Principles, Optimization, and Applications. Russ. J. Electrochem. 38(8), 919–926.

[38] Huang, C.H., Xu, T.W., Zhang, Y.P., Xue, Y.H. and Chen, G.W., 2007. Application of electrodialysis to the production of organic acids-state-of-the-art and recent developments (review). J. Membr. Sci. 288, 1-12.

[39] Kappel, C., Yasadi, K., Temmink, H., Metz, S.J., Kemperman, A.J.B., Nijmeijer, K., Zwijnenburg, A., Witkamp, G.J. and Rijnaarts, H.H.M., 2013. Electrochemical phosphate recovery from nanofiltration concentrates. Sep. Purif. Technol. 120, 437 - 444.

[40] Zhang, Y., Pinoy, L., Meesschaert, B., Van der Bruggen, B., 2013. Phosphate separation and recovery from wastewater by novel electrodialysis. Environ. Sci. Technol. 47, 5888 - 5895.

[41] Mahvi A. H., Shafiee F., Naddfi K., 2005. Feasibility study of crystallization process for water softening in a pellet reactor. Int. J. Environ. Sci. Technol. 1, 301-304.

[42] Montastruc L., Azzaro-Pantel C., Biscans B., Cabassud M., Domenech S., Dibouleau L., 2003. A general framework for pellet reactor modeling: Application to P-recovery. 9th Congress of the French Society of Chemical Engineering, Saint-Nazaire, France, 9–11 September.

[43] Zhou P., Huang J., Alfred W.F.LI and Wei S., 1999. Heavy metal removal from wastewater in fluidized bed reactor. Water Res. 33, 1918-1924.

[44] Aldaco, R., Irabien A., Luis, P., 2005. Fluidized bed reactor for fluoride removal. Chem. Eng. J. 107, 1 – 3, 113 – 117.

[45] Van Houwelingen, G., Bond, R., Seacord, T., Fessler, E., 2010. Experiences with pellet reactor softening as pretreatment for inland desalination in the USA. Desalin. Water Treat. 13, 259 - 266.

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