Resource Reclamation Through Municipal Wastewater: A review

Gopalakrishnan Sarojini[1*], G. Santhi[2], G. Sasireka[3], P Kannan[4], G. Mahendran[5]

[1]Department of Food Technology, Dhaanish Ahmed Institute of Technology, Coimbatore, Tamil Nadu, India.

[2] Department of Chemistry, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamil Nadu, India.

[3]Department of Chemical Engineering, Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, India.

[4] Department of Chemistry, V.S.B College of Engineering Technical campus, Coimbatore, Tamil Nadu, India.

[5]Department of Petrochemical Technology, RVS College of Engineering and Technology, Coimbatore, Tamil Nadu, India.

Abstract : Water is an important part of our life. Demand for water is increasing owing to increase in population, urbanization and industrialization. Most of the developing countries consumes Tonnes of water per day and about 75% of waste is discarded as contaminated outflow. This produces a hazard to the ecosystem. By means of proper treatment and management, resources could be recovered from waste effluent and converted. Also recycling provides offers financial advantage. Various technologies are available for recovery of resources. This review explains the various resources recovered from municipal wastewater.

Keywords: *Municipal water; Resources; Phosphorous; Ammonia; Nitrogen; Nutrients*

1.Introduction

With advances in recent technology, municipal waste waster should be considered as resources and source of fresh water rather than viewing it as waste. Treatment of municipal waste water should be aimed at recovering instead of removing. The ultimate aim of wastewater treatment plant is to convert wastewater into clean water before discharging into aquatic water bodies. Due to vast industrialization and rapid population growth scarcity for water is increasing enormously. Present water resources could not satisfy entire demand and could satisfy only 60% of water demand. However, most of the water resources depend on the seasonal rainfall and location. Most of the industries are also discharging untreated effluent into water resources thereby water sources are being depleted.

Though numerous innovative technologies are providing its way to recover resource from municipal waste water, adsorption technique offer the most potential to recover more valued resources from wastewater. Heavy metals, radioactive metals, pharmaceutical products, hormones, fertilizers, nutrients and bioplastics could be recovered from municipal waste water using adsorption process. The process of adsorption have admirable benefits including higher efficiency, lesser energy consumption, lower operating capital, easy operation with simple maintenance and lesser investment. Furthermore appropriate processes were to be implemented in municipal waste water treatment plants. Implementation of special featured advanced techniques is necessary.

Conventionally, the main aim to treat wastewater is covert wastewater into clean water ensured with standards that the discharge does not harm human health and water bodies. As the distribution of water resources depends on season and geographic location, efforts are made being made to tap water sources from wastewater recovery. About 50% of treated municipal water is discharged is discharged into waste water bodies [1]. The need for municipal water is continuously increasing every year. However, reclamation of municipal wastewater reduces the cost of delivery and prevents further pollution on transport. Reclamation of municipal wastewater is more economical compared with seawater desalination. Also, retrieval of clean water from municipal wastewater is being documented as sustainable water management strategy. This review discuss the recovery of various sources namely organic content, nutrient, phosphorous, nitrogen and ammonium from munical wastewater.

2.Recovery of organic content

In India, the presence of organic content in municipal sewage water is predicted by the parameter of COD and BOD varying in the range of 200-900 ppm and 100-400 ppm respectively. The organic content could be removed by adsorption column in pre-treatment method. Two types of columns namely packed bed column and batch stirred tank column is used to remove organic matter. Compared to batch stirred tank column, packed bed adsorber is highly efficient due to higher packed density [2]. Normally, in pre-treatment process itself, the organic matters get adsorbed on the surface of packed adsorbant. Thus, the organic matter in the sewage water was removed and level of COD get reduced. Also, the recovery of organic matter from sewage water improves the economy of the treatment process by reducing the pollutant content.

3. Nutrient recovery

Municipal wastewater is source rich of concentrated nutrients and trace nutrients. Nitrogen and phosphorous are concentrated nutrients. Ammonia is a widely used fertilizer and has been processed by Haber process. Phosphorous and nitrogen are also widely used fertilizers in agriculture. Agriculturists use large quantity of phosphorous and nitrogen in form of fertilizer. Therefore, their availability in soil is more and enter into water bodies. It is estimated that 81 % of phosphorous and 79 % of nitrogen is available in municipal wastewater. Most of them have not been recovered and reused for valuable usage. It is important to recover nutrients from municipal wastewater. It is noteworthy that reuse of recovered nitrogen as fertilizer saves energy as well as reduces the need for producing chemicals for synthesizing commercial fertilizer. Recovery and reuses of nutrients improves the sustainability in agriculture as it facilitates the economic growth in production of fertilizer. Adsorption is most commonly used approach to recover nutrients from municipal wastewater.

Aqua -species including macro algae or microalgae, duckweed, wetland plants are used as adsorbents. The nutrients gets adsorbed on the surface of the adsorbents and more than 60% of nutrients are recovered by this kind of planktons. In this method a synergy exists between recycling of nutrients and purification of water. However, it is very cost and energy intensive.

4. Recovery of phosphorous

Considering the critical demand of phosphorous for fertilizer and depletion of phosphorous resources, recovery of phosphorus from waste is very significant. Phosphorous is removed from wastewater via ion exchange adsorption. In this process, phosphate (PO_4^{3-}) ions from wastewater gets adsorbed on Phosphorous selective solid media. This media has tendency to exchange PO_4^{3-} with cations Cl^- to produce phosphorous depleted water and maintains neutral charge in the media. It reported that about 15% of phosphate could be recovered from wastewater and could effectively satisfy demand for phosphate fertilizer [3]. Normally these solid media are highly porous substances with relatively large surface area and adequate active sites to adsorb ions [4]. Numerous commercial adsorbents such as pyrolite A500P, A520E, Amberlite IRA-410, hybrid anion exchangers, and hydrotalcite products have been employed as adsorbent to recover phosphorous.

Most of the reported literature studies stands as evidence for recovery of phosphorous from both real and synthetic wastewater [5]. Removal of phosphorous was performed in various feed concentration even at very low concentration to 2000 mg/L [6]. The process has been extended to industrial effluents with traces of phosphorous [7]. The recovery of phosphorous depend on the selectivity of adsorbents, species of competing ions, feed concentration and phosphate concentration [8]. Adsorption capacity of HAIX media gets affected for feed with high concentration (160 mg/L) of sulphate ions. Previous literature reported that presence of active sites decides the adsorption capacity of HAIX media and therefore regeneration of HAIX media is very important as it minimizes the operation cost as well as waste generation [9]. The regeneration of HAIX media is usually accompanied with lower volume of alkaline or brine solution. The desorption of phosphorous highly depends on nature of regenerant and the process of regeneration. Regeneration can be carried out in simple or two step process. Single stage regeneration accompanies the usage of single solution and finds its application in large scale owing to low cost of chemicals, simple process and flexibility.

Typically, sodium chloride, magnesium chloride and mixture of sodium chloride and sodium hydroxide are most commonly employed desorbing agents. The extent of desorption of phosphorous from HAIX media depends on regenerant volume. However, it is impossible to achieve complete desorption and also the adsorption capacity gets reduced on repeated usage of regenerated HAIX media. It reported that about 70% adsorption capacity gets reduced after 3 cycle of adsorption-desorption process. Most of the literature reports that minimum loss has occurred in adsorption capacity even after 10 cycles [10].

Phosphorous is recovered from regenerated solution by precipitation. Up on addition of calcium nitrate or mixture of magnesium sulphate and ammonium chloride, the phosphorous precipitates out. However, for further reuse of spent regenerant, the addition of sodium hydroxide is required to compensate the loss of hydroxyl ions in precipitation process. Also trace concentration of phosphorous affects the adsorption capacity of recycled regenerant.

Phosphorous can be removed from real, synthetic and municipal waste water by using magnetic microsorbents. Microsorbents are suspended magnetic materials. The nutrients get adsorbed on magnetic media and recovered under high-power magnetic field. Ferromagnetic zirconium ferrite, carbonyl iron particles, magnetite and iron oxide nanoparticles embedded in silicon oxide matrix coated with P selective ZnFeZr are the most commonly employed microsorbents. These microadsorbents have the ability to adsorb 99% phosphorous and could reduce the phosphorous level to below 0.005 mg/L [11]. For instance, in another research ZnFeZr was employed as adsorbent to recover phosphorous from wastewater and conveyed that adsorbent possessed an adsorption capacity of 88%.). In one research study, the applicability of MgFe-Zr as adsorbent was reported in pilot scale treatment of sewage effluent [12]. It was reported that of MgFe-Zr adsorbent attained a adsorption efficiency of 88% and desorption efficiency of 95% in removal of phosphorous [13]. In order to achieve improved efficiency, it is recommended to apply with higher dosage of adsorbent. Magnetic ion exchange resins can also be used to recover phosphorous [14]. Desorption of microsorbents was carried out by using alkaline solution or mixture of 1M sodium hydroxide and 1M sodium chloride.

5. Recovery of Nitrogen

The removal of nitrogen in municipal wastewater is important because it prevents eutrophication of water bodies. Ammonia nitrification and denitrification are most commonly employed conventional techniques in removal of nitrogen. Recently developed process, Anammox converts ammonium and nitrate into nitrate under anaerobic conditions. However, all the above said processes do not recover nitrogen and but returns back nitrogen to atmosphere.

6. Recovery of ammonium

Adsorption is most commonly employed to recover ammonia from wastewater. Adsorbents like natural and synthetic zeolite, clinoptilolite, clay, bentonite, hydrotalcite, montmorillonite and mordenite are most preferred adsorbents applied for recovery of ammonia [15]. Comparatively, zeolites find vast application owing to being highly efficient, simplicity in handling cum operation and economically competitive [16]. Zeolite obtained from rice husk ash showed higher adsorption capacity of 46.56 mg/g than that of mordenite with of 15.13 mg/g [17]. Normally, Zeolite is a type of aluminosilicate mineral with large inner surface area. Moreover, the structure of zeolite is porous with many active sites for adsorbing ammonium ions and composed of Al^{3+}, Si^{4+} and oxygen containing functional groups with exchangeable cations to attract ammonium ions [18]. Negatively charged aluminosilicate framework and electrostatic interaction are responsible for cation exchange capability. Zeolites of various types including natural Chinese zeolite, Iranian zeolite and Australian zeolite with porous size of 0.07-0.2 mm exhibited an adsorption capacity of 5.05-12.6 mg/g [19]. Few reports evidenced that zeolites and clinoptilolite possessed the adsorption capacity in the range of 3.11 to 13.73 mg/g [20]. These findings suggest that applicability of natural adsorbents to remove ammonium from municipal wastewater is not satisfactory as their adsorption capacity is very low.

Researchers developed surface modified adsorbents via surface coating, chemical activation and physical activation methods. Chemical activation includes the treatment of adsorbents with acids, alkali and salt. Physical activation is treatment under microwave or heat treatment. These treatment methods increases the functional groups, cations and active sites on the surface of the adsorbent which in turns improves the adsorption capacity towards ammonium [21]. Few studies report that chemically modified zeolite possess higher adsorption capacity compared with natural zeolite. For instance, zeolite NaY was prepared from rice husk ash and compared its adsorption capacity with natural mordenite. The team reported that the prepared zeolite displayed ammonium adsorption capacity of 3 fold higher than mordenite [22]. Like so, zeolite synthesized from fly ash by solvent free method possessed an adsorption capacity of 18.4 mg/g [23].

Like zeolite, few adsorbents also show weaker affinity to ammonium suggesting the need for modification to improve the adsorption capacity to handle municipal wastewater with low-concentration ammonium. The adsorption capacity of clinoptilolite was explored and reported that adsorption capacity could be improved on pretreatment with sodium hydroxide. Also, the removal efficiency depends on pH, adsorbent dosage, temperature and initial ammonium concentration.

Attainment of equilibrium between ammonia and ammonium is controlled by pH and it facilitates the removal of ammonium ions [24].

Bentonite exhibited very low adsorption capacity of 5 mg/g for initial ammonium concentration of 50 mg/. Chitosan coated bentonite was synthesized and reported the adsorption efficiency was increased to 11.6 mg/g at initial ammonium concentration of 266.4 mg/L [25].

However, synthesis and modification of natural zeolites is hard and complicated. Replacement of Si^{4+} by cations showed improved adsorption capacity. After activation with NaCl, zeolite adsorption capacity improved to 1.5 times greater than that of natural zeolite [26]. The performance of micro-wave treated Chinese zeolite in removal of ammonium was investigated and compared its adsorption capacity with thermal treated zeolite. Chinese zeolite was modified treating with 2.5 mol/L NaCl irradiated under microwave at 119 W and 2450 MHz [26]. Thermal treated zeolite was obtained under treatment with 2.5 mol/L NaCl solution under controlled temperature of 65°C. It was reported that adsorption capacity of both modified zeolites increased to 10.61 and 11.59 mg/g whereas naked zeolites displayed an adsorption of 6.96 mg/g. Modified zeolite was synthesized from fly ash by means of alkail fusion hydrothermal method to adsorb ammonium and found that modified zeolite exhibited an very high adsorption capacity of 23.89 mg/g. In another study, the performance of zeolite particles entrapped in polyvinyl alcohol-alginate was explored and reported that the adsorption capacity increased to 4.3 times higher than naked zeolite [27]

Therefore, for adsorption of ammonium from low-concentrated municipal wastewater, it is recommended to use modified zeolite rather than natural zeolite. However economic concerns must be considered to validate economic viability and environmental sustainability.

Recent adsorbents including carbon nanotubes, Romanian volcanic tuff and wheat straw emerged as an alternative to zeolites. New adsorbent named palygorskite nanocomposite displayed an adsorption capacity of 237.6 mg/g in removal of ammonium due to the presence of carboxyl functional groups in the polymer matrix and equilibrium was achieved within 12 min [28]. Few studies report that the adsorbent could be used as a slow-release fertilizer. Presence of competing cations reduces the adsorption capacity. Very few studies reported zeolites had an ability to remove both nitrogen and phosphorous simultaneously from concentrated wastewater [29]. It was reported that phosphorous was eliminated by means of precipitation with hydroxyapatite whereas calcium precipitates out. Moreover, ammonium was removed by adsorption on zeolites. The spent zeolite was recommended for usage of green fertilizer. The zeolites are regenerated on treatment with concentrated or thermal regeneration process.

7. Different adsorption process configuration for recovery of ammonia

Various Engineering process have been developed for recovery of ammonia through adsorption. In most of the conceptualized process, adsorption was incorporated as pretreatment for municipal wastewater treatment [30]. In this process about 70-80% of ammonium ions was removed by adsorption and almost 15% was eradicated through biological assimilation. In most cases, adsorption was proposed after upstream operations. However, the proposal could not be followed in real time application of organic removal as the microbes present in the effluent might contaminate the adsorbent through surface adsorption. In such cases regeneration of adsorbent is complicated and difficult. To overcome these difficulties, an anaerobic membrane bioreactor coupled with zeolite adsorption unit for removal of ammonium ion was developed [31]. The particles and soluble nutrients are removed from effluent by membrane and then undergoes adsorption process. Reverse osmosis unit removes further residual organics from the effluent. This process can be applied to effluent with very low concentration (<1 mg/L). The ammonium sorbed adsorbents are regenerated and reused by recovering adsorbed ammonium. In most cases, adsorption occurs by cation exchange.

Numerous studies have been carried out to investigate the performance of adsorption as an appropriate tool for recovery of ammonium from municipal wastewater. Most of the available adsorbents possess less adsorption capacity, low selectivity and regeneration is also difficult. Also, economic constraints are being faced in large application of ammonium recovery from municipal wastewater via adsorption.

8. Removal of volatile organic compounds

Currently anaerobic technologies are employed to treat municipal wastewater. In anaerobic digestion process, biogas is released from organic matter. Biogas is a mixture of gases containing 60-65% CO_2, 35-40%, 5% H_2S, N_2, H_2, traces of O_2, CO, NH_3 and volatile organic compounds. The composition of biogas depends on nature of organic pollutants, the physicochemical conditions of the digester and presence of nitrates and sulfates in the pollutant. Also the composition of biogas varies according with nature of wastewater. For example, biogas produced on treatment of municipal wastewater is composed of 70-80% nitrogen, 10-25% nitrogen and 5-10% carbon dioxide [32]. Higher proportion of nitrogen is due to presence of dissolved nitrogen in municipal sewage. Normally, nitrogen is stripped in the gaseous form in anaerobic digestor. Hydrogen sulphide and CO_2 are removed by adsorption.

Volatile organic compounds are produced during microbial degradation of organic matter and are responsible for unpleasant odour. Volatile organic compounds are removed by the process of adsorption in a fixed bed regenerative bed. The bed consists of two or columns with activated carbon. The gaseous volatile organic compounds adhere to the surface of adsorbent through weal intermolecular forces. Activated carbon is the commonly used adsorbent for removal of volatile organic compound. Silica gel, zeolite and alumina are few adsorbents employed to remove volatile organic compounds. The adsorbents are activated under high temperature under controlled conditions of heat floe to remove volatile non -carbon matter. The regeneration is accomplished by lowering the pressure column or increasing the adsorbent temperature by steam flow

9. Future Perspectives

Municipal wastewater is being considered as an alternative for renewable source of fresh water. Biological oxidation-reduction process is employed to convert ammonium to nitrogen gas. Biological oxidation-reduction process is highly costly and also generates huge amount of greenhouse gases. However, this process is grounded on the perception of linear economy and its primary objective is to satisfy the discharge standard effluent. It does not concentrate on the recovery and reuse of nutrients. In future, technology has to be developed with primary motive of recovery of energy, resources and freshwater. In future research should be focused on selective and efficient recovery of resources particularly phosphorus and nitrogen. Technology adopted should ensure scale up focusing on more recovery efficiency, product quality and reduction in operational cost. Water reuse is another advantage. Integration of Advanced membrane technology will increase the safety of treated water for agricultural applications. Apart from conventional resources, biopolymers, biochar, polymers and trace metals also present in municipal wastewater. Incorporation of novel recovery pathways will increase the economic viability of wastewater valorization. Artificial Intelligence, process automation and real time monitoring will assure for control, flexibility of recovery for variable wastewater characteristics and provides optimization.

10. Conclusions

The release of nutrients rich wastewater into aquatic system caused eutrophication. Therefore, to avoid environmental issues, the minimal level of nutrients in wastewater should be stringently. Also, recovery of nutrients contributes a major role in circular economy and conservation of resources. The resources that are present in municipal wastewater and that could be recovered through treatment have been outlined. Presence of resources in various concentration range and recovery level are represented. Recovery of many resources depends on the technology adopted. A single technology cannot achieve high recovery rate. Therefore, combination of technologies permits recovery of various resources.

11. References

1. P. Rajasulochana, V. Preethy, Comparison on efficiency of various techniques in treatment of waste and sewage water – a comprehensive review, Resour. Technol. 2 (2016) 175–184, https://doi.org/10.1016/j.reffit.2016.09.004.
2. Goodwin, D., Raffin, M., Jeffrey, P., & Smith, H. M. Informing public attitudes to non-potable water reuse: The impact of message framing. *Water Research*. 2018, 145, 125–135. https://doi.org/10.1016/j.watres.2018.08.014
3. Mousavi, S. M., M. A. B. Siddique, M. R. M. Reza, M. A. H. Bhuiyan, M. S. Hossain, M. A. S. Mollah, and M. M. Rahman, Biodegradation of synthetic dyes by bacterial strains. *Environmental Technology & Innovation*. 2021, 23, 101674. https://doi.org/10.1016/j.eti.2021.101674
4. Shinde, P. A., S. S. Shinde, S. S. Shinde, and S. S. Shinde, An integrated approach of adsorption and membrane processes for the removal of contaminants from wastewater. *Environmental Technology & Innovation*, 23, 101674. https://doi.org/10.1016/j.eti.2020.101674
5. Sousa, Carlos Y., Annabel Fernandes, Albertina Amaro, Maria José Pacheco, Lurdes Ciríaco, and Ana Lopes, Electrochemical recovery of phosphorus from simulated and real wastewater: Effect of investigational conditions on the process efficiency. *Sustainability*, 15(24), 16556
6. Brandão, A. T. S. C., State, S., Costa, R., Enache, L.-B., Potorac, P., Vázquez, J. A., Valcarcel, J., Silva, A. F., Enachescu, M., & Pereira, C. M. (2023). Porous Carbon Materials Based on Blue Shark Waste for Application in High-Performance Energy Storage Devices. *Applied Sciences*, 13(15), 8676. https://doi.org/10.3390/app13158676
7. Kaljunen, J. U., Al-Juboori, R. A., Khunjar, W., Mikola, A., & Wells, G. (2022). Phosphorus recovery alternatives for sludge from chemical phosphorus removal processes – Technology comparison and system limitations. *Sustainable Materials and Technologies*, 34, e00514. https://doi.org/10.1016/j.susmat.2022.e00514
8. Sengupta, S., & Pandit, M. (2011). Selective removal of phosphorus from wastewater combined with its recovery as a solid-phase fertilizer. *Water Research*, 45(8), 2439–2449. https://doi.org/10.1016/j.watres.2011.02.015
9. Sousa, Carlos Y., Inês Gomes, Albertina M. Marques, and Annabel Fernandes (2025). Phosphorus recovery from industrial effluents through chemical and electrochemical precipitation: A critical review. *Environmental Science and Pollution Research*, 32(1), 377–396. https://doi.org/10.1007/s11356-025-09727-5
10. Zheng, Dianyuan, Rongbin Yao, Chengxiang Sun, Yuhang Zheng, and Cheng Liu (2021). Highly Efficient Low-Concentration Phosphate Removal from Aqueous Solutions Using a Composite Adsorbent. *ACS Omega*, 6(5), 3597–3605. https://doi.org/10.1021/acsomega.0c05489
11. Johir, M. A. H., S. M. Rahman, S. K. K. R. S. Mollah, and A. K. SenGupta (2011). Phosphorus recovery from wastewater using hybrid anion exchange (HAIX) resin. *Environmental Technology*, 32(10), 1111–1119. https://doi.org/10.1080/09593330.2010.536703
12. Pinelli, D., Bovina, S., Rubertelli, G., Martinelli, A., Guida, S., Soares, A., & Frascari, D. (2022). Regeneration and modelling of a phosphorus removal and recovery hybrid ion

exchange resin after long-term operation with municipal wastewater. *Chemosphere*, 286, 131581. https://doi.org/10.1016/j.chemosphere.2021.131581

13. Ding, L., Wu, C., Deng, H., & Zhang, X. (2012). Adsorptive characteristics of phosphate from aqueous solutions by MIEX resin. *Journal of Colloid and Interface Science, 366*(1), 1–6. https://doi.org/10.1016/j.jcis.2011.10.018
14. Pap, S., Kirk, C., Bremner, B., Sekulić, M. T., Shearer, L., Gibb, S. W., & Taggart, M. A. (2023). Pilot-scale phosphate recovery from wastewater to create a slow-release fertilizer using chitosan-calcite adsorbent. *Science of The Total Environment*, 870, 161656. https://doi.org/10.1016/j.scitotenv.2023.161656
15. Gupta, V. K., Ali, I., Saleh, T. A., Siddiqui, M. N., & Agarwal, S. (2015). Removal of toxic metals from aqueous solutions by ion-exchange resins: A review. *Journal of Industrial and Engineering Chemistry, 21*, 1–11. https://doi.org/10.1016/j.jiec.2014.11.013
16. Huang, J., Rathnayake Kankanamge, N., Chow, C., Welsh, D. T., Li, T., & Teasdale, P. R. (2018). Removing ammonium from water and wastewater using cost-effective adsorbents: A review. *Journal of Environmental Sciences*, 63, 174–197. https://doi.org/10.1016/j.jes.2017.11.017
17. Yusof, A. M., Lee, K. K., Ibrahim, Z., Abdul Majid, Z., & Nik Ahmad Nizam. (2010). Kinetic and equilibrium studies of the removal of ammonium ions from aqueous solution by rice husk ash-synthesized zeolite Y and powdered and granulated forms of mordenite. *Journal of Hazardous Materials, 174*(1-3), 538–544. https://doi.org/10.1016/j.jhazmat.2009.09.067
18. Saltali, K., Sari, A., & Aydın, M. (2007). Removal of ammonium ion from aqueous solution by natural Turkish (Yildizeli) zeolite for environmental quality. *Journal of Hazardous Materials, 147*(3), 1183–1188. https://doi.org/10.1016/j.jhazmat.2007.01.053
19. Huang, J., et al. (2018). Ammonium removal from aqueous solutions by natural and synthetic zeolites: A review. *Environmental Science and Pollution Research*, 25(8), 7614–7631. https://doi.org/10.1007/s11356-018-1281-5
20. Murkani, M., Nasrollahi, M., Ravanbakhsh, M., Bahrami, P., & Jaafarzadeh Haghighi Fard, N. (2015). Evaluation of natural zeolite clinoptilolite efficiency for the removal of ammonium and nitrate from aquatic solutions. *Environmental Health Engineering and Management Journal, 2*(1), 17–22. https://ehemj.com/article-1-60-en.pdf
21. Soetardji, J. P., Claudia, J. C., Ju, Y. H., Hriljac, J. A., Chen, T. Y., Soetaredjo, F. E., Santoso, S. P., Kurniawan, A., & Ismadji, S. (2015). Ammonia removal from water using sodium hydroxide modified zeolite mordenite. *RSC Advances, 5*(84), 83689–83699. https://doi.org/10.1039/C5RA15419G
22. Liu, Y., Yan, C., Zhang, Z., Wang, H., Zhou, S., & Zhou, W. (2018). Synthesis of zeolite P1 from fly ash under solvent-free conditions for ammonium removal from water. *Journal of Hazardous Materials, 344*, 1–9. https://doi.org/10.1016/j.jhazmat.2017.10.042
23. Vassileva, P., & Voikova, M. (2009). Investigation on natural and pretreated Bulgarian clinoptilolite for ammonium removal from aqueous solutions. *Desalination*, 249(1), 241–245. https://doi.org/10.1016/j.desal.2008.11.016
24. Angar, Y., Djelali, N.-E., & Kebbouche-Gana, S. (2017). Investigation of ammonium adsorption on Algerian natural bentonite. *Environmental Science and Pollution Research, 24*(11), 10780–10788. https://doi.org/10.1007/s11356-017-8696-1
25. Gaouar Yadi, M., Benguella, B., Gaouar-Benyelles, N., & Tizaoui, K. (2016). Adsorption of ammonia from wastewater using low-cost bentonite/chitosan beads. *Desalination and Water Treatment*, 57(45), 21444–21452. https://doi.org/10.1080/19443994.2015.1111250

26. Zhang, W., Liang, Z., Ni, J., Liu, J., Wang, J., Li, J., Li, Z., Zhang, Y., & Zhang, Y. (2016). Improving the ammonium ion uptake onto natural zeolite by using an integrated modification process. *Environmental Science and Pollution Research, 23*(2), 1234–1243. https://doi.org/10.1007/s11356-015-5375-2
27. Lei, L., Li, X., & Zhang, X. (2008). Ammonium removal from aqueous solutions using microwave-treated natural Chinese zeolite. *Separation and Purification Technology, 58*(3), 359–366. https://doi.org/10.1016/j.seppur.2007.05.008
28. Putra, R. N., & Lee, S. (2020). Entrapment of micro-sized zeolites in porous hydrogels: Strategy to overcome drawbacks of zeolite particles and beads for adsorption of ammonium ions. *Chemical Engineering Journal*, 398, 125687. https://doi.org/10.1016/j.cej.2020.125687
29. Zheng, Y., et al. (2014). Highly efficient adsorption of ammonium onto palygorskite nanocomposite and evaluation of its recovery as a multifunctional slow-release fertilizer. *Chemical Engineering Journal*, 248, 1–9. https://doi.org/10.1016/j.cej.2014.03.060
30. Lin, L., et al. (2014). Ammonium assists orthophosphate removal from high-strength wastewaters by natural zeolite. *Chemical Engineering Journal*, 248, 1–9. https://doi.org/10.1016/j.cej.2014.03.060
31. Cruz, H., Laycock, B., Strounina, E., Seviour, T., Oehmen, A., & Pikaar, I. (2020). Modified poly(acrylic acid)-based hydrogels for enhanced mainstream removal of ammonium from domestic wastewater. *Environmental Science & Technology, 54*(11), 6882–6892. https://doi.org/10.1021/acs.est.0c01035
32. Godifredo, J., Ferrer, J., Seco, A., & Barat, R. (2023). Zeolites for nitrogen recovery from the anaerobic membrane bioreactor permeate: Zeolite characterization. *Water*, 15(6), 1007. https://doi.org/10.3390/w15061007