Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 10, October : 2024

Zero Liquid Discharge for Sustainable Water Management: A Comprehensive Review

P.Kalpana*1, J. Raja Murugadoss[1], T.Venumadhav[1], P.King[2]
[1] Department of Civil Engineering, Audisankara College of Engineering and Technology, Gudur, AP, India
[2] Department of Chemical Engineering, Andhra University College of Engineering, AP, India
*corresponding author: drkalpanabastian@gmail.com

Abstract:
Zero Liquid Discharge (ZLD) is a cutting-edge strategy aimed at achieving sustainable water management by eliminating liquid waste from industrial processes. This review explores the various technologies and methodologies employed in ZLD systems, focusing on their applications in different industries, including lignocellulosic biorefineries, thermal power plants, and chemical industries. It discusses the critical role of advanced treatment techniques like membrane filtration, evaporative processes, and crystallization in recovering valuable resources from wastewater while ensuring environmental protection. The review also examines challenges related to energy consumption, cost-efficiency, and scalability of ZLD solutions, as well as emerging innovations like machine learning and automation to optimize performance. Through a comprehensive analysis, this review underscores ZLD's potential to revolutionize water sustainability, aligning industrial water practices with global environmental goals.

Key Words: *Waste water Treatment, Membrane technology, zero liquid discharge, reverse osmosis*

1. Introduction:

In recent years, the escalating demand for freshwater resources coupled with increasing concerns about environmental sustainability has prompted a paradigm shift in industrial and municipal water management practices. ZLD has emerged as a pivotal and innovative solution to address water scarcity and minimize the environmental impact of wastewater discharge [1,2]. ZLD represents a comprehensive approach wherein the goal is to recover as much water as possible from industrial processes, leaving no liquid effluent to be discharged. This technique involves a combination of advanced water treatment technologies, including membrane filtration, evaporation, crystallization, and ion exchange, to achieve a closed-loop system. As industries and municipalities worldwide grapple with the challenge of balancing water consumption with conservation efforts, a thorough review of the state-of-the-art ZLD technologies and their application in sustainable water management becomes imperative [3,4].

The impetus for a comprehensive review lies in the need to critically evaluate the efficacy, challenges, and advancements in ZLD systems across various industrial sectors. Understanding the economic viability, environmental impact, and regulatory compliance associated with ZLD implementations is crucial for informing future policies and practices [5]. Moreover, this review aims to provide insights into the evolving landscape of sustainable water management and how ZLD contributes to achieving a harmonious balance between industrial processes and environmental stewardship. By synthesizing existing literature and highlighting key technological and regulatory trends, this review seeks to serve as a valuable resource for researchers, policymakers, and industry professionals working towards sustainable water practices in the 21st century. This review aims to provide an overview of the principles underlying ZLD, examine the various technologies employed in ZLD processes, and assess the environmental and economic benefits of ZLD.

ZLD is a water management approach that involves the complete elimination of liquid discharge from a system, ensuring that no wastewater is released into the environment. A typical ZLD plant and key elements involved in plant is shown in Fig 1.

Fig1. ZLD Plant and Key components

1.1.Key Components:

Pretreatment: Removal of contaminants and impurities.

Pretreatment plays a pivotal role in the ZLD process by serving as the initial line of defense against contaminants and impurities present in industrial wastewater [6-7]. As a critical phase in the ZLD system, pretreatment involves the targeted removal pollutants, suspended solids and other undesirable substances to enhance the efficiency of subsequent water treatment processes. By addressing the challenges associated with feedwater quality, pretreatment safeguards the integrity and longevity of ZLD technologies such as membrane filtration, evaporation and crystallization. Effective pretreatment not only ensures the reliable performance of downstream units but also mitigates scaling and fouling issues, thereby optimizing the overall ZLD system for sustainable and responsible water management practices across diverse industrial applications [8].

Concentration: Achieving high solute concentrations through evaporation or other methods.

Concentration stands as a crucial stage in the ZLD process, wherein the aim is to achieve elevated solute concentrations by reducing the volume of wastewater through evaporation or other specialized methods. Employing technologies such as multiple-effect evaporators or mechanical vapor recompression, the concentration phase concentrates dissolved solids in the remaining liquid, facilitating subsequent recovery and minimizing the discharge of liquid waste [9-10]. This pivotal step not only contributes to the efficient utilization of resources but also enhances the overall effectiveness of ZLD systems. By concentrating the solutes prior to the final steps of crystallization or other separation processes, ZLD ensures a more sustainable approach to water management, emphasizing resource recovery and environmental responsibility across diverse industrial sectors [11].

Crystallization: Precipitation of salts and minerals for recovery.

Crystallization stands as a pivotal process in the ZLD framework, involving the controlled precipitation of salts and minerals from the concentrated solution, with the ultimate goal of recovering these valuable substances [12]. This phase is instrumental in achieving the zero liquid discharge objective by transforming the concentrated brine into solid crystals, leaving behind virtually no liquid waste. Through carefully managed conditions of temperature and pressure, crystallization facilitates the selective separation of salts, enabling their subsequent collection for potential reuse or responsible disposal. The crystallization step not only embodies a resource recovery aspect but also serves as a key contributor to the overall sustainability of ZLD systems, marking a critical advancement in the responsible treatment and management of industrial wastewater [13-14].

Dewatering: Separation of solids from concentrated brine.

Dewatering plays a pivotal role in the ZLDprocess by focusing on the separation of solids from the concentrated brine, ultimately contributing to the achievement of zero liquid discharge goals [15]. This stage involves the removal of remaining water from the concentrated brine or slurry, reducing its volume and increasing the concentration of solids. Various dewatering techniques, such as filtration or mechanical methods, are employed to extract moisture from the concentrated solution, leaving behind a solid cake or residue. Efficient dewatering not only aids in the reduction of waste volume but also enhances the potential for resource recovery from the separated solids [16]. By effectively managing the separation of solids in the concentrated brine, the dewatering phase stands as a critical component in the ZLD process, aligning with sustainable water management practices and minimizing the environmental impact of industrial wastewater discharge.

2.Technologies in Zero Liquid Discharge:

2.1 Membrane Technologies:

Reverse Osmosis (RO)

Reverse osmosis (RO) technology plays a pivotal role in achieving ZLDin industrial and environmental settings. ZLD is an innovative approach aimed at minimizing wastewater generation and maximizing water recovery, thereby addressing the escalating water scarcity concerns [17-18]. In the context of ZLD, reverse osmosis serves as a key component by effectively removing dissolved impurities and contaminants from wastewater. This process involves the application of pressure to push water through a semi-permeable membrane, selectively allowing water molecules to pass while blocking the passage of salts, minerals, and other pollutants. The result is a purified water stream that can be further treated or reused, while the concentrated brine containing the removed impurities is managed separately. By harnessing reverse osmosis within the framework of ZLD, industries can significantly reduce their environmental impact, conserve water resources, and comply with stringent wastewater discharge regulations. This integration of advanced water treatment technologies underscores the importance of sustainable practices in water management for a more resilient and environmentally conscious future [19].

Forward Osmosis (FO)

Forward osmosis (FO) technology is emerging as a promising solution within the context of ZLDstrategies. Unlike reverse osmosis, which uses pressure to separate water from contaminants, forward osmosis employs osmotic pressure differentials to draw water through a semi-permeable membrane, leaving impurities behind [20]. In the ZLD framework, forward osmosis presents a unique advantage by requiring lower energy inputs compared to traditional methods. This process is particularly effective in concentrating wastewater, producing a more manageable brine stream for further treatment or disposal. Forward osmosis is versatile, allowing for the extraction of water from challenging industrial effluents with high salinity or complex chemical compositions. By integrating forward osmosis into ZLD systems, industries can enhance water recovery, reduce environmental impact, and adhere to sustainable water management practices. This technology contributes to the broader goal of achieving water sustainability by maximizing resource efficiency and minimizing the ecological footprint of industrial processes [21].

Nanofiltration (NF)

Nano filtration (NF) technology stands at the forefront of innovation in ZLD initiatives, providing a highly effective means of separating water from impurities with molecular precision [22]. In ZLD applications, nano filtration plays a crucial role by selectively allowing certain ions and molecules to pass through its membrane, while rejecting others based on size and charge. This results in a purified water stream while retaining divalent ions and larger organic molecules. NF is particularly adept at addressing the challenges posed by industrial effluents with medium to high salinity levels. By harnessing the capabilities of nano filtration within ZLD systems, industries can achieve a more efficient water recovery process, reducing the volume of wastewater and minimizing environmental impact [23]. The advanced filtration capabilities of NF contribute to a sustainable approach to water management, aligning with the global imperative to conserve and reuse water resources in the face of increasing water scarcity and stringent environmental regulations.

2.2 Evaporation Techniques:

Multiple Effect Evaporation (MEE)

Multiple Effect Evaporation (MEE) technology plays a pivotal role in the realm of ZLDstrategies, offering an efficient means of concentrating and recovering valuable water from industrial wastewater. In the MEE process, heat is applied to a series of evaporator vessels, each operating at progressively lower pressures [24]. This cascading effect allows for the utilization of the vapor generated in one stage to provide the energy needed for subsequent stages, leading to significant energy savings compared to single-effect evaporation. MEE proves especially effective in handling high-salinity effluents common in industrial processes, producing a concentrated brine stream that can be managed separately. By incorporating Multiple Effect Evaporation within ZLD systems, industries can achieve substantial reductions in wastewater volume and minimize the environmental impact of effluent discharge. This technology aligns with sustainability goals, promoting the circular economy by recovering and reusing water resources in an era where water scarcity is a pressing global concern [25].

Mechanical Vapor Compression (MVC)

Mechanical Vapor Compression (MVC) technology stands as a cornerstone in the implementation of ZLD solutions, providing an energy-efficient means of evaporating and recovering water from industrial wastewater. In the MVC process, water vapor is generated by compressing and heating the vapor from the evaporator, thereby concentrating the wastewater and producing a high-quality distillate [26]. What distinguishes MVC is its ability to reuse the latent heat of vaporization, minimizing the need for external energy sources and making it a more sustainable option compared to traditional evaporation methods. This technology is particularly effective in managing wastewater with high salinity or challenging compositions. By incorporating Mechanical Vapor Compression into ZLD systems, industries can significantly reduce the volume of discharged wastewater, mitigate environmental impact, and optimize resource utilization. This approach not only aligns with regulatory compliance but also addresses the escalating global water scarcity crisis by promoting the efficient recovery and reuse of water resources in industrial processes.

Falling Film Evaporation (FFE)

FFE technology is a key player in the implementation of ZLD strategies, offering an efficient and compact solution for concentrating industrial wastewater. In FFE, the liquid flows as a thin film over a vertical surface, and heat is applied to induce evaporation [27]. This method is particularly effective for high-salinity or challenging industrial effluents, as it allows for the concentration of dissolved solids while producing a high-quality distillate. FFE offers advantages in terms of energy efficiency, as the falling film design minimizes the resistance to heat transfer. The compact nature of FFE systems makes them suitable for integration into ZLD frameworks, aiding in the reduction of wastewater volume and the recovery of valuable resources. By leveraging Falling Film Evaporation technology in ZLD applications, industries can enhance their sustainability efforts, comply with stringent environmental regulations, and contribute to the conservation of water resources in the face of growing global water scarcity concerns.

2.3 Crystallization Methods:

Forced Circulation Crystallization

Forced Circulation Crystallization (FCC) technology stands as a crucial component within the realm of ZLD solutions, offering an effective means of recovering valuable water from industrial wastewater while minimizing environmental impact. In the FCC process, a specialized pump circulates a super-saturated solution, inducing the controlled crystallization of dissolved salts and minerals [28-29]. This selective separation of solids from the liquid phase allows for the generation of a high-purity distillate stream, while the concentrated brine can be managed separately. FCC technology is especially well-suited for handling wastewater with high salinity and challenging compositions. By integrating Forced Circulation Crystallization into ZLD systems, industries can achieve significant reductions in wastewater volume and the responsible management of effluent. This approach aligns with sustainability goals, conserving water resources and promoting environmentally conscious practices in a world where water scarcity and regulatory compliance are paramount concerns.

Cooling Crystallization

Cooling Crystallization technology plays a pivotal role in the realm of ZLD, offering an effective solution for concentrating industrial wastewater and recovering valuable resources. In this process, the temperature of a supersaturated solution is reduced, leading to the controlled crystallization of dissolved solids [30]. As the crystals form, they can be separated from the liquid phase, producing a high-purity distillate. This approach is particularly well-suited for industrial effluents with high concentrations of salts and minerals. Cooling Crystallization allows industries to efficiently manage and reduce wastewater volume while obtaining valuable by-products in the form of crystals. By incorporating Cooling Crystallization into ZLD systems, companies can achieve significant strides in water conservation, environmental sustainability, and regulatory compliance. This technology exemplifies an innovative and responsible approach to industrial wastewater management, aligning with the global imperative to minimize the ecological footprint of industrial processes and ensure the efficient use of water resources.

Anti-Solvent Crystallization

Anti-Solvent Crystallization technology is a cutting-edge method integral to ZLD strategies, offering a sophisticated approach to concentrate and recover valuable water from industrial wastewater [31]. In this process, an anti-solvent is introduced to a solution, causing a reduction in solubility and triggering the crystallization of dissolved solids. The formed crystals can then be separated from the liquid phase, yielding a high-quality distillate. This technology is particularly effective for treating wastewater with complex chemical compositions, including challenging industrial effluents with high solute concentrations. Anti-Solvent Crystallization not only facilitates water recovery but also allows for the extraction of valuable by-products in crystalline form. By incorporating Anti-Solvent Crystallization into ZLD systems, industries can significantly reduce the discharge of wastewater, adhere to environmental regulations, and contribute to sustainable water management practices [32]. This innovative technology reflects a forwardlooking approach to industrial processes, emphasizing resource efficiency and responsible water utilization in the face of growing water scarcity concerns.

3.Environmental and Economic Benefits:

3.1 Reduced Environmental Impact:

Preventing water pollution and conserving water are vital for sustainable environmental management. Strict regulations on industrial discharges, advanced wastewater treatment technologies, and public education on responsible waste disposal are essential to safeguard water quality. Concurrently, water conservation efforts, such as water-saving technologies, reforestation, and recycling systems, reduce demand and preserve ecosystems, ensuring a sustainable water supply for future generations.

3.2 Resource Recovery:

ZLD processes not only minimize wastewater but also recover valuable by-products like salts and metals, supporting both environmental sustainability and economic viability. The reuse of treated water within industrial operations further reduces freshwater intake and promotes resource efficiency, fostering a circular economy.

3.3 Economic Viability:

ZLD systems offer cost savings by reducing water consumption and minimizing disposal costs. Additionally, industries can generate revenue by recovering and selling valuable by-products from the treatment process. This combination of cost reduction and resource recovery makes ZLD a financially and environmentally sound solution

4. Challenges

4.1 Technical Challenges:

Energy Consumption in ZLD Processes: One of the critical considerations in the implementation of ZLD processes is the energy consumption associated with various treatment technologies. ZLD typically involves energy-intensive processes such as reverse osmosis, multiple-effect evaporation, and mechanical vapor compression. Reverse osmosis, in particular, requires a significant amount of energy to pump water through semi-permeable membranes. Mechanical vapor compression systems, while effective in minimizing liquid discharge, can also demand substantial energy inputs. Balancing the benefits of water recovery and resource conservation with the energy requirements is crucial in designing sustainable ZLD systems. Innovations in energy-efficient technologies and the integration of renewable energy sources, such as solar or waste heat recovery, are increasingly being explored to mitigate the environmental impact of ZLD processes and make them more economically viable in the long run [33].

Management of Residual Brine: A key challenge in ZLD systems is the management of residual brine, the concentrated solution left after water recovery processes. This brine often contains high levels of salts and other dissolved solids, making its proper disposal or utilization critical. Discharging brine directly into water bodies can harm aquatic ecosystems due to elevated salinity levels. Therefore, responsible management strategies are essential [34-35]. In some cases, the brine can be further treated or processed to recover valuable salts or minerals, providing an economic incentive. Additionally, innovative approaches, such as the integration of crystallization technologies, can help solidify the brine into manageable solids for disposal or reuse. Efficient management of residual brine is vital for the overall success and environmental sustainability of ZLD systems, ensuring that the benefits of water recovery are not offset by the environmental impact of concentrated brine disposal.

5.Conclusion:

The increasing global population has been a significant factor in the water consumption of the sector during the last ten years, and this trend is anticipated to continue in the years to come. The notion of internal water recycling is made possible by the ZLD that is required due to the disparity between the supply and demand of industrial water. With an average water recovery of 90–95% recorded, the majority of ZLD systems now in use rely on biological, membrane, and thermal processes for industrial effluent pretreatment, concentration, evaporation, and crystallization.

This comprehensive review underscores the significance of ZLD as a sustainable and efficient approach to water management. By examining its principles, technologies, benefits, and challenges, this paper contributes to the ongoing dialogue on responsible water use and environmental stewardship. As we face unprecedented water challenges, ZLD stands out as a key player in shaping a more sustainable and resilient future.

References:

1. Li J, Ma J, Dai R, Wang X, Chen M, Waite TD, Wang Z (2021), "Self-enhanced decomplexation of Cu-organic complexes and Cu recovery from wastewaters using an electrochemical membrane filtration system". Environ. Sci. Techno, Vol.55,20221, pp 655–664.

2. Tong T& Elimelech M (2016), "The global rise of zero liquid discharge for wastewater management: Drivers, technologies, and future directions", Environ. Sci. Technol, Vol. 50, 2016, pp.6846–6855.
3. Yaqub M, Lee W(2019), "Zero-liquid discharge (ZLD) technology for resource recovery from wastewater: A review". Sci. Total. Environ, Vol. 681, 2019, pp.551–563.
4. Mukherjee M & Jensen O (2020), "Making water reuse safe: A comparative analysis of the development of regulation and technology uptake in the US and Australia", Saf. Sci, Vol.121, 2020, 121, pp. 5–14.
5. Panagopoulos A& Haralambous K J (2020), "Minimal liquid discharge (MLD) and ZLDstrategies for wastewater management and resource recovery—Analysis, challenges and prospects". J. Environ. Chem. Eng, Vol.8, 2020, pp 104418.
6. Zhang C,Ma J, Wu L, Sun J, Wang L, Li T (2021), "Waite, T.D. Flow electrode capacitive deionization (FCDI): Recent develop-ments, environmental applications, and future perspectives" Environ. Sci. Technol, Vol. 55, 2021,pp 4243–4267.
7. Liu Y, Liu F, Ding N, Hu X, Shen C, Li F, Huang M (2020), "Recent advances on electroactive CNT-based membranes for environmental applications: The perfect match of electrochemistry and membrane separation. Chin. Chem. Lett, Vol. 31, 2020, pp 2539–2548.
8. Xiong R &Wei C (2017), "Current status and technology trends of zero liquid discharge at coal chemical industry in China", J. Water Process. Eng., Vol 19, 2017, pp. 346–351.
9. Mohammadtabar F, Khorshidi B, Hayatbakhsh A, Sadrzadeh M (2019), "Integrated coagulation-membrane processes with ZLDconfiguration for the treatment of oil sands produced water" Water, Vol. 11, 2019, pp. 1348.
10. Semblante G U, Lee J Z, Lee L Y, Ong S L, Ng H Y (2018), "Brine pre-treatment technologies for zero liquid discharge systems". Desalination , Vol. 441, 2018, pp. 96–111.
11. Wu Q, Li W T, Yu, W, Li Y, Li, AM (2016), "Removal of fluorescent dissolved organic matter in biologically treated textile wastewater by ozonation-biological aerated filter". J. Taiwan Inst. Chem. Eng, Vol 59, 2016, pp 359–364.
12. Gupta S K & Gupta, S (2018), "Closed loop value chain to achieve sustainable solution for tannery effluent" J. Clean. Prod, Vol. 213, 2018, pp. 845–846.

13. Lin H, Gao W, Meng F, Liao B Q, Leung, K T, Zhao L, Chen J, Hong H (2012), "Membrane bioreactors for industrial wastewater Treatment: A critical review" Crit. Rev. Environ. Sci. Technol, Vol.42, 2012, pp. 677–740.
14. Haberkamp, J, Ruhl, A.S, Ernst, M, Jekel, M (2007), "Impact of coagulation and adsorption on DOC fractions of secondary effluent and resulting fouling behaviour in ultrafiltration", Water Res, Vol. 41, 2007, pp. 3794–3802.
15. Breitner L N, Howe K J, Minakata, D (2019), " Effect of functional chemistry on the rejection of low-molecular weight neutral organics through reverse osmosis membranes for potable reuse" Environ. Sci. Technol, Vol 53, 2019, 11401–11409.
16. Zhang C, Li J, Chen Z, Cheng F (2017), "Factors controlling adsorption of recalcitrant organic contaminant from bio-treated coking wastewater using lignite activated coke and coal tar-derived activated carbon" J. Chem. Technol. Biotechnol, Vol.93, 2017, pp 112–120.
17. Yuan Y, Xing G, Garg S, Ma J, Kong X, Dai P, Waite T D (2020) "Mechanistic insights into the catalytic ozonation process using iron oxide-impregnated activated carbon" Water Res. Vol. 177, 2020, pp115785.
18. Liu Z Q, Huang, C, Li JY, Yang J, Qu B, Yang, SQ, (2021), "Activated carbon catalytic ozonation of reverse osmosis concentrate after coagulation pretreatment from coal gasification wastewater reclamation for zero liquid discharge" J. Clean. Prod Vol. 286, 2021, pp 124951
19. Loganathan K, Chelme Ayala, P, El-Din M G (201), " Treatment of basal water using a hybrid electrodialysis reversal–reverse osmosis system combined with a low-temperature crystallizer for near-zero liquid discharge" , Desalination , Vol. 363, 2015, , pp. 92–98.
20. Wang Z, Feng D, Chen Y, He D, Elimelech M (2021) "Comparison of energy consumption of osmotically assisted reverse osmosis and low-salt-rejection reverse osmosis for brine management" Environ. Sci. Technol. Vol. 55, 2021, pp. 10714–10723.
21. Othman Z A, Linke P, Elhalwagi M M A (2015), " Systematic Approach for Targeting Zero Liquid Discharge in Industrial Park" Computer Aided Chemical Engineering; 2015; pp. 887–892.
22. Cui P, Qian Y, Yang S (2018), " New water treatment index system toward zero liquid discharge for sustainable coal chemical processes" ACS Sustain. Chem. Eng, Vol.6,2018, pp. 1370–1378.

23. Garcia Herrero I, Margallo M, Onandía R, Aldaco R, Irabien A (2018), "Connecting wastes to resources for clean technologies in the chlor-alkali industry: A life cycle approach" Clean Technol. Environ. Policy, Vol.20, 2018, pp. 229–242.
24. Zhang C, Ma J, Waite T D,(2020) " The impact of absorbents on ammonia recovery in a capacitive membrane stripping system" Chem. Eng. J. 2020, 382, 122851.
25. Zhang C, Ma J, He D, Waite T D, (2017) "Capacitive membrane stripping for ammonia recovery (CapAmm) from dilute wastewaters. Environ" Sci. Technol. Lett. 2017, 5, 43–49.
26. Zhang, C, Ma, J, Song, J, He, C, Waite, T.D. Continuous ammonia recovery from wastewaters using an integrated capacitive flow electrode membrane stripping system. Environ. Sci. Technol, Vol.52, 2018, pp.14275–14285.
27. Dongare P, Alabastri A, Pedersen S, Zodrow K R, Hogan N J, Neumann O, Wu J, Wang T, Deshmukh A, ElimelechM (2017) "Nanophotonics-enabled solar membrane distillation for off-grid water purification." Proc. Natl. Acad. Sci. USA, Vol.114, 2017, pp. 6936–6941. [
28. Ma J, Ma J, Zhang C, Song J, Dong W, Waite TD (2020), " Flow-electrode capacitive deionization (FCDI) scale-up using a membrane stack configuration" Water Res. Vol.168, 2020, 115186.
29. Liu Y, Gao G, Vecitis CD (2020), "Prospects of an Electroactive Carbon Nanotube Membrane toward Environmental Applications". Accounts Chem. Res. Vol.53, 2020, pp. 2892–2902.
30. Zheng J, Wang Z, Ma J, Xu S, Wu Z (2018), "Development of an electrochemical ceramic membrane filtration system for efficient contaminant removal from waters" Environ. Sci. Technol. Vol.52, 2018, pp 4117–4126.
31. Zheng J, Ma J, Wang Z, Xu S, Waite, T.D, Wu, Z(2017)"Contaminant removal from source waters using cathodic electrochemical membrane filtration: Mechanisms and implications" Environ. Sci. Technol. Vol. 51,2017, pp. 2757–2765.
32. Chaplin B P (2019) "The prospect of electrochemical technologies advancing worldwide water treatment" Accounts Chem. Res. Vol.52, 2019, 596–604.
33. Gupta I, Vachasiddha L, Kumar R (2017) Evaluation of the costs and benefits of mumbai sewage disposal project, India. Indian J Geo- Marine Sci 46:1539–1545
34. Paul R, Kenway S, Mukheibir P (2019) "How scale and technology influence the energy intensity of water recycling systems-an analytical review" J Clean , Vol. 215, 2019pp.1457–1480

35. Singh N K, Kazmi A A (2018) "Performance and cost analysis of decentralized wastewater treatment plants in Northern India: case study" J Water Resour Plan Manag, Vol. 144, 2018, pp. 1–9