Indian Journal of Experimental Biology
Vol. 58, August 2020, pp. 508-514

Minireview

Zero Liquid Discharge (ZLD) as Sustainable Technology — Challenges and Perspectives

Anil V. Shah[1,2], Sunita Varjani[1,2,*], Vijay Kumar Srivastava[2] & Ashish Bhatnagar[3]

[1]Gujarat Pollution Control Board, Sector-10A, Gandhinagar-382 010, Gujarat, India
[2]Sankalchand Patel Vidyadham, Sankalchand Patel University, Visnagar-384 315, Gujarat, India
[3]Sun Pharmaceuticals Industries Ltd., Panoli-394 116, Gujarat, India

Received 31 January 2020; *revised 27 February 2020*

In sustainable treatment of wastewater, in addition to treatment performance, other aspects viz. energy utilization, recycling of wastewater and social issues also play vital role in evaluation of the sustainability. It is useful for achieving zero liquid discharge from industries. Soil biotechnology (SBT) is a type of biological treatment that plays major part in zero liquid discharge (ZLD) technology. ZLD is used for conversion of organic matter present in wastes into various grades of products for soil application and turns wastewater to cleaner water in the presence of selective geophagus earthworms, bacterial culture and formulated soil. SBT reduces the level of various pollutants in industrial wastewater *viz.* biological oxygen demand, chemical oxygen demand, ammonium nitrate, phosphates, nitrogen, suspended solids, odour, colour and other undesired organisms. This review briefly discusses the need for sustainable development in treatment of wastewater. It also provides an updated scientific literature on zero liquid discharge systems in industries including challenges and perspectives.

Keywords: Biofertilizer, Crystallization, Effluent treatment, Industrial pollution, Reverse osmosis, Sludge, Soil biotechnology, Sustainable development, Wastewater treatment

Rapid industrialization to meet the demands of the modern society and life style results in increased energy consumption[1,2]. in general, we have two types of energy sources: (a) renewable; and (b) non renewable[3,4]. Renewable energy sources are solar energy, hydropower energy, wind energy, geothermal energy and biomass. Non renewable energy sources are coal, petroleum, natural gas and radioactive energy. These sources are classified as (a) non-polluting energy sources; and (b) polluting energy sources[5]. Non-polluting energies are called as green energies as they do not cause any environmental pollution during utilization. Industrialization is one of the major causes of depletion of global resources such as clean water and air[3,5-9].

Environment, economy and wellness are connected with each other, particularly for last three decades since when the concept of sustainable development came into existence[8,10,11]. When looking towards sustainable development in different ways, distinctive types of scientific aspects on sustainability in the initial stages cannot be ignored. The main concept of sustainable development is based on environment, development and future security[5,7,12,13]. Security is related to conflicts and also covers social matters in terms of income and medical care. The most important angles in sustainable development are economic, environment and social culture[8,10]. Approach of sustainable development should include all resources like social and environmental values as primary principle. However, practical analysis includes the financial costs and benefits[4,12,14,15]. Economic sustainability mainly focuses on increasing human well-being, through optimal allocation and distribution of scarce resources, to meet and satisfy human needs[10,11,12,16]. The long period sustainability of environment required to be maintained to support the development by providing resources and reducing emissions[17-19]. This should result in protection and proper utilization of resources. Environmental sustainability refers to capability of environment to sustain human life without compromising environment health[8,11,15]. Social, spiritual and cultural needs in an impartial way, with balance in human relationships, morality, and institutions is a need of hour[19,20]. This dimension

*Correspondence:
Phone: +91 9909828684 (Mob.)
E-mail: drsvs18@gmail.com

builds upon human relations, the need for people to interact, to develop themselves, and to organize their society. Sustainable development is an interlinkage of three systems — social, biological and economical, with aim to optimize across these systems taking into account, the strengths and weaknesses[8,10,16]. Sustainable development on industrial wastewater treatment and disposal varies with the location[4,8,9]. Studies indicate that gross products production increase with per capital growth which leads to increase in waste and wastewater. Waste management is important for conservation of available natural resources and protect the environment for sustainable development[19]. In industries, sustainable wastewater treatment plays vital role to achieve zero liquid discharge (ZLD)[4,5]. In this review, we focused on soil biotechnology (SBT) as one of the most important part of zero liquid discharge (ZLD) technology. SBT is used for the conversion of organic matter of wastes into various product grades for soil application. By this technology, wastewater is converted into clean water using earthworms, bacterial culture and formulated soil. Need for sustainable development, zero liquid discharge wastewater systems in industries and challenges and perspectives in this field have been discussed in detail.

Need for sustainable development

Sustainability means finding solutions for balancing the energy consumption with different resources such as environment, economic and culture in such a way that it minimizes conflicts[10]. These solutions help to eliminate the current conflict issue and also assist in controlling global future challengess[8]. Water and fuel are major issues of current concern[5]. The sustainable technologies should be effectual and provide appropriate solution against minimum carbon footprint.[3] Carbon footprint can be defined as quantity of carbon dioxide released into atmosphere due to |activities of any individual, organization or community[3,10].

Fig. 1 schematically depicts sustainable technology. In the first step of sustainable development it is required to translate needs of end user into function and that must complete with the technologies. Technological step is combination of social cultural, physical and economical environment. These factors are interrelated at different levels depending on the basis of the conflict. It is crucial to make an overview of how the conflicts interact with other factors i.e. problems and solutions[19].

Sustainable technology development and waste management

Sustainable technologies on waste management include 4R principle i.e. refuse, reduce, reuse and recycle. Introducing technology to extend production rate with reduced raw material volume and maximum outputs with higher efficiency is development[19]. Generated waste should be treated under 'end-to-end pipe treatment' technologies, and also it is important to manage waste by various technologies for compliance of different industries[5,8]. Sustainable techniques for waste management can be categorized into physical, chemical, biological and theological parts. Ecofriendly management of waste requires combination of cost and energy effective technologies[5,21]. Sustainable treatment of waste involves such consistent processes or techniques which do not harm the environment directly or indirectly, and also help to sustain the socio-culture and economy by possible recovery of raw materials through recycling.

Zero liquid discharge

Zero liquid discharge (ZLD) is defined as wastewater management system ensuring no discharge of industrial wastewater in the environment. Simply, it is a closed loop with no liquid discharge. It can be achieved through treatment of wastewater by recycling, recovering and reusing. It is a part of sustainable environment development which is capable of minimizing the contamination of water stream, particularly in industrial applications. ZLD is ideal technology for treatment of toxic industrial waste, minimizing waste and reuse of water to mitigate natural resource However high cost and

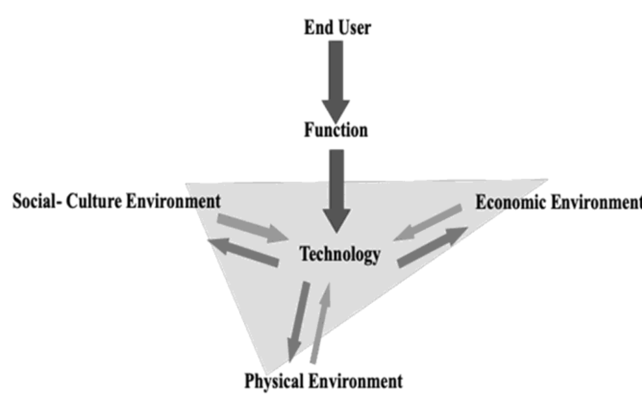

Fig. 1 — Schematic diagram of sustainable technology

intensive constipation of energies are issues of concern with ZLD[4,5].

Assessing sustainability in industries for ZLD wastewater systems

Sustainability and development are two sides of a coin. To achieve sustainable solution for industrial wastewater systems, we need to compare a wide variety of systems with respect to sustainability[5,12,21]. Different measures that can be used for assessing sustainability involves exploration of methodologies viz., exergy and economic analyses including life cycle assessment and system analysis.

Exploration of methodologies

Exploration of methodologies utilizes the results of earlier research work done on environment friendly or sustainable water systems, e.g. attempts to measure/identify sustainability using single indicator e.g. Energy and/or Economic analysis have been used. Other commonly used methodologies apply application more than one indicator e.g. Life cycle assessment and/or system analysis[4,5].

Exergy analysis

Exergy is defined as the part of energy which carry out mechanical work. Exergy analysis is a thermodynamic type of analysis based on second law of thermodynamics and expresses quality of an exergy flow[22]. It provides another option to compare and assess the systems and processes rationally and meaningfully. Comparing various wastewater systems based on exergy is an example this analysis. Benefit of exergy analysis is that the entire comparison is based on a single absolutely determinable indicator i.e. energy, different indicators have not been given weightage in exergy analysis[23]. Though it gives a vision on efficiency of the process, it doesn't provide any insight on the environmental impacts[8,22].

Economic analysis

The economic analysis proposes a single indicator approach. It is considered as compelling case to express sustainability in terms of money. Money is used as budgetary indicator to take any decision[11,22]. Life cycle expense, Cost-benefit analysis, and Total price assessment are the tools to assess the balances that are expected to have costs and benefits and are often the first step in any industrial project. In theory, all kinds of costs and benefits can be included. However, in practice, these tools are mostly used as a one-dimensional technique which incorporate only financial costs and benefits[8,23].

Life cycle assessment (*LCA*)

It is developed to assess environmental impacts encountered during lifetime of product. This method starts with defining aim and scope of the proposed study, and utilizes the life cycle inventory environmental aspects based on energy and mass balances[24]. The environmental aspects are categorized into various categories having environmental impacts such as desiccation, depletion of ozone, degradation of landscape, depletion of resources, eutrophication, acidification, global warming potential and ecotoxicity[13]. These categories are assessed to make a decision of feasibility of technology, either to be chosen or rejected.

System analysis

Here, with the use of energy and mass balance, necessary equations are designed to indicate the application of material, emissions in the environment, energies used, and land area required for operation. In principle, life cycle assessment is one kind of system analysis and an integrated method based on mass and energy equilibrium which uses indicators which in LCA are named as impact categories. LCA is commonly applied for comparison of technologies on environmental impacts only. Whereas system analysis as a whole assesses the process in general and gives a summary as it captures the nature of system in a mathematical description[13,24].

The above enlisted methodologies lead towards new vistas when applied to urban water system. Economic analysis, exergy analysis and life cycle assessment provide highlights into real costs, energy efficiency and impacts on environment, respectively[13,24]. Whereas the system analysis provides more detailed approach comprising various factors through use of self-defined sustainability such as cost, impact on environmental, exergy and social as well as cultural aspects[13,18,23].

Developing a model-based decision support tool for ZLD

Although ZLD is a large carbon footprint generation process, it paves the way for economic sustainability through resource recovery. Scarcity of water, regulations for environment and water economics motivate ZLD system at large. ZLD system can be employed with deferent processes such as Thermal, membrane processes (Reverse osmosis), pretreatment (Biological — Convection effluent treatment plant)[4,5,21,25-28].

Thermal processes

These processes use evaporators and crystallizers to achieve ZLD. Evaporators treat wastewater by heating the wastewater and the volatile compounds from the wastewater are allowed to cool down which leads to production of cleaner water by condensation. The objective of this process is to concentrate non-volatile solutes such as inorganic salts, organic compounds and leave behind more concentrated wastewater. There are some common industrial wastewater evaporator(s) e.g. mechanical vapour recompression evaporators, atmospheric evaporators and humidification-dehumidification evaporators[25,29,30].

Membrane processes

Reverse osmosis (RO) is a membrane process, a separation technique, used for a wide range of applications. Particularly it is used when dissolved solids of salts are required to be removed from wastewater of the industries which leads production of cleaner water, this concentrated water is then processed for evaporation to archive ZLD[31-33]. Reverse osmosis can be also for desalination in case of sea water and brackish water[31,34]. It has been reported that due to reverse osmosis loss of minerals takes place hence remineralization after reverse osmosis is necessary eg. In the water/wastewater treatment plants, where water pipeline corrosion is a main problem, lime is generally employed for remineralization of water due to its easy availability and economic feasibility[35-37].

Pretreatment using biological processes

Biological treatment plays a vital role in any industrial wastewater treatment and forms an integral part of treatment process to achieve ZLD. It can be aerobic (in presence of air) or anaerobic (in absence of air). These two terms are related to (a) type of microorganisms leading degradation of pollutants present in wastewater; and (b) operating conditions of the bioreactor[2,9,15,18,38-41].

Soil biotechnology (SBT)

One of the most promising biological technologies for treatment of industrial wastewater is soil biotechnology. It is based on biological conversion processes. In this process, natural basic reactions such as photosynthesis, respiration and mineral weathering, that occur in the growth media due to microorganisms, results in desired purification[40,42,43]. SBT can also be referred as an oxygen providing biological source, hence process can be used for treatment of and/or domestic, municipal and industrial wastewater[44]. Fig. 2 explain various components of SBT.

Media and culture of soil biotechnology is partly weathered — the soil type having appropriate (a) primary minerals of particle size, (b) composition, (c) liquid hold up, and (d) hydraulics. Geophagus type worms such as earthworm (*Pheretima elongate*) and suitable bacterial culture act as partners in action. Appropriate culture is required to be used in particular growth conditions. Factors affecting soil biotechnology are liquid hold up, oxygen transfer, hydraulic loading, carbon and nitrogen removal efficacy of media in bioreactor bed, nitrogen fixation, residence time distribution and organic loading[40,45,46].

Soil biotechnology plant is a simple set up. The untreated water is first stored in a tank, which is later pumped into the bioreactor. After treatment, it is collected in the freshwater tank under the flow of gravity[44,46]. The tanks can be underground or overhead, made up of either brick, steel or concrete depending upon the feasibility. The bioreactor contains material having almost similar density as that of soil in it. Hence, 'no-load' bearing structures are required if the bioreactor is constructed inside the ground[45,47]. In soil biotechnology process for treatment of industrial effluents, bacterial communities form the colony on soil media use organic substances present in the wastewater as food and the end product of the process are simple compounds. On environmental perspective, soil biotechnology has not only near-zero biomass production, but also consume less energy and causes relatively less air pollution[42].

Soil biotechnology reduces pollution load in the wastewater *viz.* organic matter, odour, nitrogen, biological oxygen demand, colour, chemical oxygen demand, ammonium nitrate, suspended solids, phosphates, undesired organisms and bacteria. It also increases the oxygen level. Advantages of soil

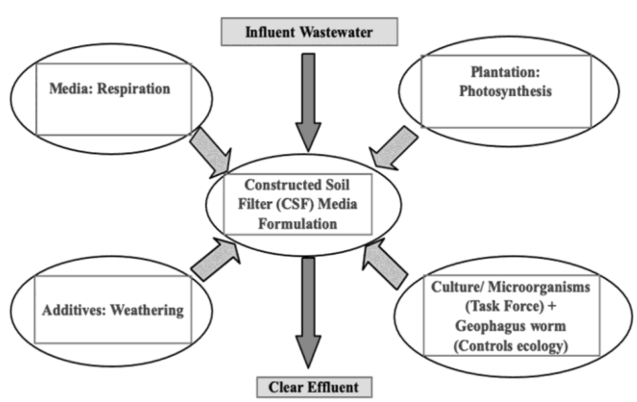

Fig. 2 — Components of SBT media

biotechnology are space saving, high efficiency, stability against shock loads and no power consumption (required for aeration). This green technology uses local materials and skills, hence it is called as an engineered green space which uses green plants as bioindicators of abnormality. SBT can handle variety of organic wastes either solid and/or liquid forms. Treated water is used in cooling water application[44,48].

Challenges and future perspectives

The challenges in existing sustainable operation of any effluent treatment plant is significantly linked to its degradation efficiency, carbon emission, biological sludge generation and energy consumption[18,21,32,47,48]. This biological treatment has to overcome the drawback of significant sludge production and air pollution over aeration for degradation to resist sustainability[20]. Sludge treatment and management accumulate approximately half of the operating energy[16,20]. Effluent treatment plants have high requirements of energy for degradation of organic matter in aeration process[6,18].

Industrial zero liquid discharge system should have low energy consumption demand including recovery of resources against treated wastewater. Hence, ZLD plant shall be developed in such a way that it is having decreased carbon footprint by treating wastewater and water reuse[44,49,50]. ZLD treatment process using soil biotechnology provides a suitable solution for development of sustainable environment[51]. ZLD has potential applications in various industries, such as pharmaceutical, textiles, dyes & pigments, sugar industries, distillery, petro-chemicals, food, dairy, fertilizers, etc[44,49,52,53].

Conclusion

Zero liquid discharge (ZLD) is a closed loop wastewater management system which can be achieved by treating wastewater through recycling, recovering and reusing. Basic treatment units of ZLD system are biological effluent treatment plant, reverse osmosis and thermal evaporation and crystallization. Soil biotechnology (SBT) is a green engineering method/approach to treat and recycle industrial wastewater. Soil biotechnology is a type of biological treatment and forms one of the important part of ZLD. Soil biotechnology treatment plant works on the principle of aerobic process mainly based on microorganisms under mechanism of attached growth process. Microorganisms decompose organic impurities present in industrial wastewater with use of oxygen and convert them into carbon dioxide, water and biofertilizer. The biofertilizer can be utilized for plant growth which are part of SBT system. After treating the wastewater with SBT system, treated wastewater can be reused in cooling tower application under high solid concentration circulation technology treatment system. SBT provides various advantages over conventional approaches which are used to treat industrial wastewater. It is based on a biological conversion process and does not generate bio sludge which is generally having fouling smell. It is maintenance free approach consuming least energy. Hence, soil biotechnology offers sustainable output to achieve ZLD with green technologies and simultaneous recovery of resources from industrial wastewater.

Conflict of interest

Authors have declared no conflict of interests.

References

1 Varjani SJ, Microbial degradation of petroleum hydrocarbons. *Bioresour Technol*, 223 (2017) 277.

2 Xu X, Liu W, Tian S, Wang W, Qi Q, Jiang P, Gao X, Li F, Li H & Yu H, Petroleum hydrocarbon-degrading bacteria for the remediation of oil pollution under aerobic conditions: A perspective analysis. *Front Microbiol*, 9 (2018) 2885.

3 Owusu PA & Asumadu-Sarkodie S, A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Eng*, 3 (2016) 1167990.

4 Yaqub M, & Lee W, Zero-liquid discharge (ZLD) technology for resource recovery from wastewater: A review. *Sci Total Environ*, 681 (2019) 551.

5 Scholz M. Sustainable Water Treatment: Engineering Solutions for a Variable Climate. 1st edn. (Elsevier, Amsterdam, Netherlands), 2019.

6 Gandiglio M, Lanzini A, Soto A, Leone P & Santarelli M, Enhancing the energy efficiency of wastewater treatment plants through co-digestion and fuel cell system. *Front Environ Sci*, (2017) 1. DOI:10.3389/fenvs.2017.00070.

7 Gupta, G, Chandra A, Varjani SJ, Banerjee C & Kumar V, Role of biosurfactants in enhancing the microbial degradation of pyrene. In: *Bioremediation: Applications for environmental protection and management* (Eds.: Varjani SJ, Agarwal AK, Gnansounou E & Gurunathan B; Springer Nature, Singapore), 2018, 375.

8 Scherer L, Behrens P, Koninga A, Heijungs R, Sprechera B & Tukkera A, Trade-offs between social and environmental sustainable development goals, *Environ Sci Policy*, 90 (2018) 65.

9 Varjani SJ & Upasani VN, Comparing bioremediation approaches for agricultural soil affected with petroleum crude - A case study. *Indian J Microbiol*, 59 (2020) 356.

10 Howarth RB & Kennedy K, 2016. Economic growth, inequality, and well-being. *Ecol Econ*, 121 (2016) 231.

11 Sauvé S, Bernard S & Sloan P, Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environ Dev*, 17 (2016) 48.

12 Summer JK, Smith LM, Case JL, Linthurst RA, A review of the elements of human well-being with an emphasis on the contribution of ecosystem services. *Ambio*, 41 (2012) 327.

13 Kim TH & Tae SH, Proposal of environmental impact assessment method for concrete in South Korea: An application in LCA (Life Cycle Assessment). *Int J Environ Res Public Health*, 13 (11) (2016) 1074. .

14 Markulev A & Long A, *On sustainability: an economic approach*. (Productivity Commission Staff Research Note, Productivity Commission, Melbourne, Australia), 2013 https://www.pc.gov.au/research/supporting/sustainability/sustainability.pdf. Accessed: 31.01.2020.

15 Mishra B, Varjani S, Kumar G, Awasthi MK, Awasthi SK, Sindhu R, Binod P, Rene ER & Zhang, Microbial approaches for remediation of pollutants: Innovations, future outlook, and challenges. *Energy Environ*, (2020) Jan. 9. Doi: 10.1177/0958305X19896781.

16 Maktabifard M, Zaborowska E & Makinia J, Energy neutrality versus carbon footprint minimization in municipal wastewater treatment plants. *Bioresour Technol*, 300 (2020) 122647.

17 Campos JL, Valenzuela-Heredia D, Pedrouso A, Val del Río A, Belmonte M & Mosquera-Corral A, Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention. *J Chem*, 9 (2016) 1. Doi: 10.1155/2016/3796352.

18 Maktabifard M, Zaborowska E & Makinia J, Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. *Rev Environ Sci BioTechnol*, 17 (2018) 655.

19 Ferronato N & Torretta V, Waste mismanagement in developing countries: A review of global issues. *Int J Environ Res Public Health*, 16 (2019) 1060.

20 Collivignarelli MC, Abbà A, Miino MC & Torretta V, What advanced treatments can be used to minimize the production of sewage sludge in WWTPs? *Applied Sci*, 9 (2019), 2650.

21 Trikoilidou E, Samiotis G, Bellos, D & Amanatidou, E, Sustainable operation of a biological wastewater treatment plant. *IOP Conf Ser: Mater Sci Eng*, 161 (2016) 012093. Doi: doi:10.1088/1757-899X/161/1/012093.

22 Terzi R, Application of exergy analysis to energy systems. *Intechopen*, (2018) 109 (Doi:10.5772/intechopen.74433; https://www.intechopen.com/books/application-of-exergy/application-of-exergy-analysis-to-energy-systems).

23 Mujan V & Aleksic S, Environmental impact of information and communication equipment for future smart grids. *Intechopen* (2019) (Doi: 10.5772/intechopen.88515).

24 Kralisch D, Otta D & Gerickea D, Rules and benefits of Life Cycle Assessment in green chemical process and synthesis design: a tutorial review. *Green Chem*, 17 (2015) 123.

25 Tong T & Elimelech M, The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. *Environ Sci Technol*, 50 (2016) 6846.

26 Assiry AM, Application of ohmic heating technique to approach near-ZLD during the evaporation process of seawater. *Desalination*, 280 (2011) 217.

27 Mohammadtabar F, Khorshidi B, Hayatbakhsh A & Sadrzadeh M, Integrated coagulation-membrane processes with zero liquid discharge (ZLD) configuration for the treatment of oil sands produced water. *Water*, 11 (2019) 1348.

28 Thamaraiselvan C & Noel M, Membrane processes for dye wastewater treatment: Recent progress in fouling control. *Crt Rev Env Sci Technol*, 45 (2015) 1007.

29 Xiong R & Wei C, Current status and technology trends of zero liquid discharge at coal chemical industry in China. *J Water Pro Eng*, 19 (2017) 346.

30 Loganathan K, Chelme-Ayala P & El-Din MG, Pilot-scale study on the treatment of basal aquifer water using ultrafiltration, reverse osmosis and evaporation/crystallization to achieve zero-liquid discharge. *J Environ Manag*, 165 (2016) 213.

31 Neilly A, Jegatheesan V & Shu L 2009. Evaluating the potential for zero discharge from reverse osmosis desalination using integrated processes - A review. *Desalin Water Treat*, 11 (2009) 58.

32 Greenlee LF, Lawler DF, Freeman BD, Marrot B, Moulin P, Reverse osmosis desalination: Water sources, technology, and today's challenges. *Water Res*, 49 (2009) 2317.

33 Viana PZ, Nobrega R, Jordão EP & de Azevedo JPS, Optimizing the operational conditions of a membrane bioreactor used for domestic wastewater treatment. *Braz Archieves Biol Technol*, 48 (2005) 119.

34 Pérez-González A, Urtiaga AM, Ibanez R & Ortiz I, State of the art and review on the treatment technologies of water reverse osmosis concentrates. *Water Res*, 46 (2012) 267.

35 Sedlak DL, The unintended consequences of the reverse osmosis revolution. *Environ Sc. Technol*, 53 (2019) 3999.

36 Liang J, Deng A, Xie R, Gomez M, Hu J, Zhang J, Ong CN & Adin A, Impact of seawater reverse osmosis (SWRO) product remineralization on the corrosion rate of water distribution pipeline materials. *Desalination*, 311 (2013) 54.

37 El Azhar F, Tahaikt M, Zouhri N, Zdeg A, Hafsi M, Tahri K, Bari H, Taky M, Elamrani M & Elmidaoui A, Remineralization of Reverse Osmosis (RO)-desalted water for a Moroccan desalination plant: optimization and cost evaluation of the lime saturator post. *Desalination*, 300 (2012) 46.

38 Mansour F, Alnouri SY, Al-Hindi M, Azizi F & Linke P, Screening and cost assessment strategies for end-of-Pipe Zero Liquid Discharge systems. *J Clean Prod*, 179 (2018) 460.

39 Slavov AK, 2017. General characteristics and treatment possibilities of dairy wastewater - A review. *Food Technol Biotechnol*, 55 (2017) 14.

40 Dutta SM, Kadam AM, Nemade PD, Oza GH & Shankar HS, Residence time distribution modeling of constructed soil filter. *Indian J Environ Protection*, 27 (2007) 769.

41 Pattanaik BR, Gupta A & Shankar HS. Residence time distribution model for soil filter. *Water Environ Res*, 76 (2004) 168.

42 Shankar HS, Patnaik BR & Bhawalkar US, US Patent No: 6890438 "Process for treatment of organic wastes, Issued May 2005.

43 Kamble SJ, Chakravarthy Y, Singh A, Chubilleau, C, Starkl M & Bawa I, A soil biotechnology system for wastewater treatment: technical, hygiene, environmental LCA and economic aspects. *Environ Sci Pollut Res*, 24 (2017) 13315.

44 Shankar HS, Patnaik BR & Bhawalkar US, US Patent No 7604742 B2 Soil Conditioning products from organic waste, Issued October 2009.

45 Varjani SJ & Upasani VN, Influence of abiotic factors, natural attenuation, bioaugmentation and nutrient supplementation on bioremediation of petroleum crude contaminated agricultural soil. *J Environ Manag*, 245 (2019) 358.

46 Nemade PD, Kadam AM & Shankar HS, Wastewater renovation using constructed soil filter (CSF): A novel approach. *J Hazard Mater*, 170 (2009) 657.

47 Nemade PD, Dutta SM & Shankar HS, Tracer dispersion in constructed soil filter for wastewater treatment. *J Nature Sci Sus Technol*, 7 (2013) 129.

48 Sihi D, Dari B (2020) Soil Biogeochemistry. In: *The Soils of India* (Ed: Mishra B) World Soils Book Series. Springer, Cham, 2020, 143.

49 Kumar PA, Online apparatus for preventing formation and deposition of hard scale in heat transfer equipment. Patent Number 2335/MUM/2009. (www.scalebanindia.com). As accessed on 31.01.2020.

50 Tufa, RA, Curcio E, Brauns E, Baak WV, Fontananova E & Profio GD. Membrane Distillation and Reverse Electrodialysis for Near-Zero Liquid Discharge and low energy seawater desalination. *J Membrane Sci*, 496 (2015) 325.

51 Kadam A, Oza G, Nemade P, Dutta S & Shankar H, Municipal wastewater treatment using novel constructed soil filter system. *Chemosphere*, 71 (2008) 975.

52 Vergili I, Kaya Y, Sen U., Gönder ZB & Aydiner C, Techno-economic analysis of textile dye bath wastewater treatment by integrated membrane processes under the zero liquid discharge approach. *Resour Conserv Recy*, 58 (2012) 25.