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Integrating the three E's in wastewater treatment: efficient design, economic viability, and environmental sustainability

Kirti M Yenkie

Water is often the most mispriced and misused component in domestic, industrial and agricultural sectors. The rise in world population and industrialization in developing nations has tremendously increased the demand for water and has resulted in the generation of wastewater which is contaminated with dangerous pollutants and unknown contaminants. Furthermore, if the wastewater is not treated properly the toxic pollutants will leach back into the ground ultimately contaminating the groundwater resources. Thus, wastewater treatment, reuse, and safe disposal have become crucial for sustainable existence. In this review, the different aspects involved in designing efficient and sustainable wastewater treatment systems such as wastewater characterization, stage-wise treatment approach, technology features, modeling methodologies, cost evaluations, and environmental impact assessment are presented and future need for information exchange, interdisciplinary collaborations and convergent research are emphasized.

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Introduction

The ever-increasing human population and industrial growth have posed a huge burden on existing resources and have led to an increase in environmental pollution and climate change. The imprudent use of water resources and overall wastes released from domestic, agricultural and industrial sectors in natural water bodies has exacerbated the challenges relating to availability, quality, and purity of water resources. Pollutants such as oxygen-demanding substances, pathogens, nutrients, inorganic, and synthetic organic chemicals have been listed as potential contaminants in municipal wastewater. Oxygen demanding substances such as ammonia pose potential dangers to aquatic life. Pathogens are carried into the groundwater through sewage sourcing from industrial waste, storm runoff, and municipal sources. Nutrients such as carbon, nitrogen, and phosphorus are found in large quantities in agricultural wastewater. If not treated properly, the large amounts of nutrients, primarily phosphorus, and nitrogen cause nutrient enrichment resulting in algae growth and eutrophication. Heat reduces the capacity of water to retain oxygen, industrial water utilized for cooling is often too hot to be released back to the ecosystem. Thus, wastewater needs to be checked and treated before it is released in the ecosystem, or else it will have detrimental effects on marine life and natural water bodies. Furthermore, freshwater resources are limited and the only way to satisfy the increased demand for water is to rely on wastewater treatment (WWT) systems that can provide reusable water or reduce contaminant concentrations to acceptable levels which can be handled by natural remediation systems (biogeochemical cycles).

Current wastewater treatment plants (WWTPs) comprises multiple treatment technologies to obtain necessary purity standards set by the regulatory agencies such as the US EPA (United States Environmental Protection Agency), European Union's Water Policy, United Nations Environmental Programme. Technologies are based on physical, biological, chemical processes or their combination [1]. Physical processes are applied for the removal of solids from wastewater usually using screens and filters. Biological processes use small organisms to remove and break down harmful sewage. Chemical processes are often combined with physical processes to remove complex pollutants. Thus, appropriate characterization of wastewater streams is essential to identify candidate technologies which will reduce the contaminants to acceptable levels.

Judicious water use and minimization in wastewater release are equally important due to the scarcity of water resources and WWTPs energy costs [2]. Considerations may include overall volume reduction, pollutant strength reduction, or a combination. Wastewater volume reduction can have a significant impact on technology capacity, flow/loadings of WWTPs, operation/maintenance costs, energy requirements, and ecological impacts. Approximately, 20–30% water savings can be achieved with flow reduction devices such as sensors for fault detections and concentration measurements, and efficient controllers [3,4]. Industrial plants can achieve wastewater volume reductions by utilizing multi-point waste collections, reuse, and elimination of sludge discharges. Finally, WWTPs need efficient design and evaluation metrics to minimize costs, energy requirements and subsequent environmental impacts while meeting the regulatory guidelines. To this end, this review summarizes the most recent developments in the areas of wastewater characterization, treatment technologies, modeling, and optimization framework for designing efficient WWTNs, economic analysis, and sustainability assessment (see Figure 1).

Wastewater characterization

The wastewater characterization includes total suspended solids (TSS), total dissolved solids (TDS), pH, organic loadings, chemical oxygen demand (COD), biochemical oxygen demand (BOD), toxic ions, active pharmaceutical ingredients (APIs), endocrine disrupting chemicals (EDCs), and others [1,5,6]. Their typical range can vary significantly based on the source of the contaminant stream. Municipal wastewater from residential sources have BOD values in the range of 100–400 mg/l, nitrogen as 20–85 mg/l and phosphorous as 6–23 mg/l [7••]. Food, drinks, and milk (FDM) sector can have effluents with 10–100 times higher BOD and COD values as compared to the municipal sector [8]. Pharmaceutical effluents contain a high concentration of organics, and APIs [9]. Thus, source of the effluent stream, its contaminant properties, and relative amounts, as well as information about limits for safe discharge or reuse of treated water enables the connection of appropriate WWT technologies to design a case-specific process flow diagram.

Treatment technologies

WWT is most effective when accomplished in stages and usually comprises preliminary, primary, secondary, and tertiary stages along with sludge treatment options [10•]. An overview of the treatment stages and technologies involved are described in Figure 2. Generally, WWTPs utilize one technology from each stage; however, depending on the purity requirements, contaminant properties and their amounts in the inlet waste stream, more than one technology might be needed in a stage or some stages might be bypassed.

The treatment results in water-rich and contaminant-rich outlet streams. The contaminant-rich stream consists of sludge which can be treated to recover nutrients via technologies such as hydrothermal liquefaction [11], thermophilic digestion [12], and fermentation, or incinerated to recover energy [13••]. The details of some existing and novel WWT technologies is provided in Table 1. This information can be used when selecting candidate technology alternatives for performing a designated task and technology network connections [7••,14••,15•].

Modeling approaches for efficient design and economic viability

WWT network (WWTN) design is a complex problem due to a high number of technology alternatives, multi-criteria design considerations of purity, costs, operational safety, and environmental impact, and lack of knowledge integration from experts. Some modeling approaches implemented in WWTN design are discussed here.

Data-driven, heuristics and performance index models

Ruiz-Rosa *et al.* [28•] proposed a data-driven Activity Based Cost (ABC) management model for WWT and reuse processes in four phases: (i) identification of final products and their measurement units, (ii) definition of product transformations and activities, (iii) relation and classification of resource groups consumed in WWT, and (iv) development of logical associations between resources, activities and products. Here, activities denote technologies, resource groups denote fixed assets, labor, energy, maintenance, social and other services, and logical associations denote cost distributions in each technology for achieving desired purity.

The work by Liu *et al.* [29•] proposed an enhancement of the numerical indicator of total mixing influence potential (TMIP) [30], based on WWT systems with minimum treatment flowrate and pinch analysis, by including heuristic rules for situations when one contaminant can be removed in multiple technologies or when multiple contaminants can be removed in a single technology. The improved model could design more complex treatment networks. Viciano *et al.* [31] introduced a performance index (Z) in the cost function to incorporate the fact that equipment does not always run on their optimal capacity due to seasonal changes, population shifts, thus impacting the energy costs. This methodology was applied to empirical data from 156 WWTPs in Valencia to represent economies of scale in efficient design and cost estimates. Fuzzy logic models, intuitional fuzzy sets and multi-criteria decision making were integrated to represent numerical and verbal information and subsequently applied to optimal WWT technology selection [15•,32].

Superstructure synthesis approaches

Garibay-Rodrigues *et al.* [33••] proposed a constraint-based MINLP (mixed-integer nonlinear programming) for integrating optimal resource management to the synthesis of distributed WWTNs. The approach is demonstrated via a typical river system that serves as a source and natural drainage to domestic, industrial and agricultural sectors with constraints of maximum allowable concentration of pollutants discharged and limit on water

Figure 1

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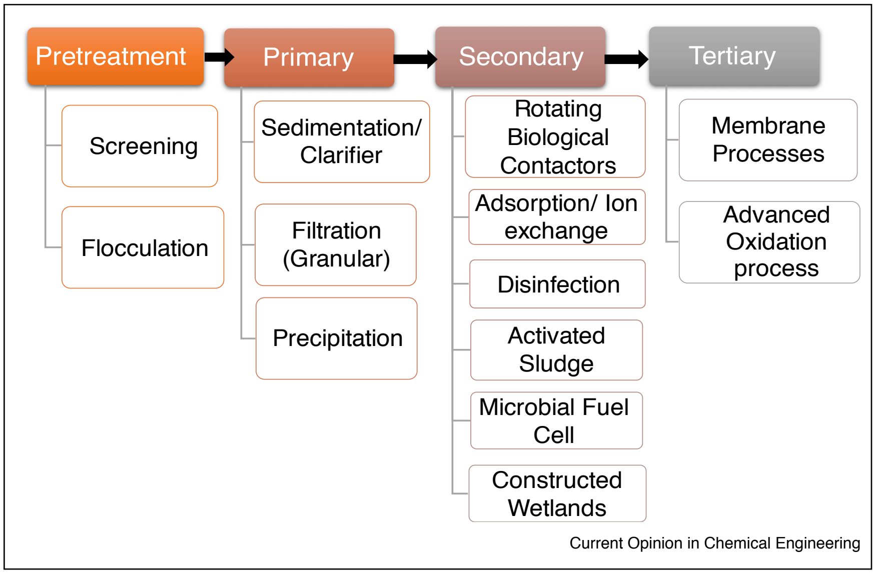
Schematic of an integrated approach for designing wastewater treatment networks. The complexity lies in the selection of appropriate technologies based on contaminants present in different sources of wastewater for treatment network synthesis followed by cost evaluations and sustainability assessment.

consumption from fresh sources and solving the total annual costs minimization problem. Alnouri *et al.* [34••] presented an approach for interplant water network synthesis in industries by combining the central and decentral treatment options and merging the common pipe segments carrying water and wastewater with similar properties, which allowed for a reduction in network complexity and overall costs.

Lu *et al.* [35••] addressed the problem of optimal synthesis and operation of WWTNs with multi-scenario influent streams under different discharge standards and penalty ratios of non-compliant emissions. They employed solution methods involving disjunctive programming, multiperiod MINLPs to minimize Total Annual Costs (TAC) to provide management insights and assist policymakers. Some other studies from the group [36,37] also

Figure 2



Stage-wise wastewater treatment design and technologies involved in each stage.

highlighted the importance of superstructure synthesis and technology modeling for WWT.

Process network synthesis approaches

Kollmann *et al.* [38••] applied the Process Network Synthesis (PNS) approach to optimize the economics of a WWTP while recovering energy in the form of heat and supplying the surplus to the public energy distribution grids. They utilized the Geographical Information System (GIS) based Energy Zone Mapping and established a feasible WWTN structure in P-graph [39] based PNS studio software. The varied applications of P-graph based PNS approach [40,41,42] indicates its potential in the field of WWTN synthesis.

Methods for sustainability assessment

Life-cycle assessment (LCA) has been the methodology of interest for many research groups [13••,43] when evaluating the sustainability of a WWTP and integrating its economics. LCA usually includes four steps: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) life cycle interpretation. Piao *et al.* [13••] demonstrated an integrated LCA and economic efficiency analysis for WWTPs and sludge management systems by subdividing them into plant operation, electricity and chemical consumption, and transport to landfills, which could prove valuable in managing urban water systems.

Kollmann *et al.* [38••] integrated the PNS and Sustainable Process Index (SPI) approaches efficiently to perform economic optimization and ecological footprints assessment of treatment technologies. Another sustainability metric, Fisher information (FI) [44•,45], was applied to capture the dynamics of multi-dimensional systems for environmental management as a single entity. WWTN design is certainly a multi-dimensional problem influenced by environmental, technological, economic, political and social factors and needs converging estimators such as FI for better projections of sustainability, resource consumption, and recovery. Value chain mapping was proposed by Chofreh *et al.* [46•] as a significant tool for practitioners in water and sewage companies to increase operational efficiency and reduce wastes by more than 50%, ultimately shifting towards more sustainable activities. Circular economy [47] and net-zero waste generation [48], or energy positive systems [49] are additional indicators used to define process sustainability.

Final remarks on integrating the 3 E's

Systematic guidelines which propose treatment based on inlet contamination and final conditions for water reuse or safe disposal will aid in designing efficient WWTNs [50••]. The treatment technologies should be appropriately placed in the network to ensure efficient contaminant removal. Novel technologies should be tested for operation at large scales and their multi-scale integration with existing technologies should be studied. Modular design based on maximal structure/superstructure synthesis comprising of all possible treatment technologies, flow patterns and connections should be applied instead of relying on conventional design and treatment methods. Non-intuitive and unconventional solutions consisting of multiple inputs and/or outputs, recycling, mixing, and

Table 1

Wastewater treatment technologies, their advantages, and limitations

Technology	Features	Advantages	Limitations
Screening [1,5]	- removes rags, paper, grit, plastics, and metals - varying screen sizes available: coarse, fine and micro	- prevents damage and clogging of downstream units	- requires regular cleaning and maintenance
Flocculation/ Coagulation [10•,16,17]	- forms flocs of suspended and colloidal particles by adding chemicals/polymers - mean residence time and recirculation ratio influences floc formation efficiency	- large flocs are easier to separate compared to their primary particle size	- cost of flocculants - mixing and time
Sedimentation/ Clarifier [5,18]	- gravitational settling based on particle terminal settling velocity given by Stokes law - tank size (area and depth), settling velocity determine the residence time	- no utility/external energy required - low cost	- tank size and time required for efficient separation
Filtration (granular) [5]	- suspended/colloidal impurities are separated via passage through a porous medium	- particle separation range higher than sedimentation	- head loss and effluent turbidity limits
Rotating biological contactors [5,19]	- a biological process consisting of reservoirs with large circular disks mounted on horizontal shaft that rotate slowly through wastewater streams - removes BOD, some phosphorus and nitrates aerates wastewater and suspended microbial growth	- simplicity, adaptability, low land use - can breakdown complex organic pollutants such as dyes	- lack of appropriate scalable systems
Adsorption/ Ion exchange [10•]	- use of a solid material such as activated carbon, selective resigns, polymeric adsorbents to remove target contaminants - can be operated in batch/ continuous modes	- simple and adaptable treatment methods - high efficiency and faster kinetics	- high capital, adsorbent, and regeneration costs - sensitive to pH
Disinfection [1]	- three main disinfection techniques; chemical (chlorine, ozone), physical (heating, chemical assisted settling), and radiation (UV, electromagnetic and acoustic) - equipment design and material costs vary based on the technique employed	- removes viruses, pathogens, and APIs in some cases	- dechlorination methods needed - performance impacted by pollutant type
Activated sludge [5,20]	- aerobic slurry consisting of microorganisms is added to the wastewater in a complete-mix suspended growth reactor - solid retention time (SRT), that is, the average time sludge remains in the system, determines the overall performance	- can degrade organic matter into CO_2, water and other end products - simple, economically favorable	- maintenance of microbial activity - poor decolorization - sludge bulking and foaming

Table 1 (*Continued*)

Technology	Features	Advantages	Limitations
Microbial fuel cells [21,22]	- utilize microbes to perform redox reactions to collect electrons from a source (harvest energy) - specific microbe rich wastewater is used to run a fuel cell resulting in water purification and electricity generation - a dual chambered system with oxygen in cathodic and microbe and organics in anodic chamber	- can treat pharmaceutical effluents - can generate energy while treating wastewater	- reactions at the anode are limiting factors - the cost of components used is very high for commercial use
Constructed wetlands [23•,24]	- engineered systems designed to use natural functions of vegetation, soil, and organisms to treat wastewater - act as a biofilter and can remove pharmaceutical and personal care products along with organics, minerals, suspended solids and pathogens	- combination of sanitation and water purification - low cost and maintenance	- species selection and maintenance are important to ensure long-term functionality
Advanced oxidation process [25,26]	- utilizes oxidation/ photo-Fenton reactions to degrade pollutants into smaller constituent molecules - agents used include ozone, peroxide, UV light, Fenton's reagents	- can be used for degrading APIs and EDCs	- high energy input for ozone and UV - lack of scalable systems
Membrane processes [10•,27]	- pressure based filtration using semi-permeable membranes - membrane pore size varies depending on the particle/ molecular size of contaminant - includes microfiltration (MF – 0.1 to 1 μm), ultrafiltration (UF – 0.01 to 0.1 μm), nanofiltration (NF – 1 to 10 nm), reverse osmosis (RO – 0.1 to 1 nm), dialysis and electrodialysis	- wide range of availability and applications - compact, no chemicals required	- clogging and fouling - high investment and membrane replacement costs

segregation of streams should be analyzed for cost effectiveness and environmental impacts. Potential risks, safety and uncertainty considerations should also be incorporated to test the robustness of the predicted optimal WWTNs. To this end, interdisciplinary collaborations, information exchange and comparative assessments through multiple approaches should be employed to eliminate existing drawbacks and provide insights into novel WWT solutions with enhanced process **E**fficiency, leading towards **E**conomic viability and **E**nvironmental sustainability.

Conflict of interest statement

The authors declare no conflict of interest.

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- • of special interest
- •• of outstanding interest

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This article presents an integrated approach for the design of WWTNs and demonstrates a comparison of results obtained from superstructure based MINLP optimization approach and the maximal structure generation and ranked list of solutions obtained from the P-graph based approach. Both the approaches provide comparable results, but P-graph solutions provide insights into some non-intuitive aspects of network synthesis.