This article is published in the *Clean Technologies and Environmental Policy journal:*

Kalbar, P.P. Hybrid treatment systems: a paradigm shift to achieve sustainable wastewater treatment and recycling in India. *Clean Technologies and Environmental Policy* (2021). https://doi.org/10.1007/s10098-021-02034-x

Hybrid Treatment Systems: A paradigm shift to achieve sustainable wastewater treatment and recycling in India

Pradip P. Kalbar[1,2,*]

[1]Centre for Urban Science and Engineering (CUSE), Indian Institute of Technology Bombay,
[2]Interdisciplinary Programme in Climate Studies, Indian Institute of Technology Bombay
Powai, Mumbai 400 076, Maharashtra, India

[*] **Corresponding Author:**
Pradip P. Kalbar,
Centre for Urban Science and Engineering (CUSE), Indian Institute of Technology Bombay,
Powai, Mumbai 400 076, Maharashtra, India
kalbar@iitb.ac.in

ORCID: 0000-0002-1436-3609

Abstract:

This study assesses a trade-off between Mechanized Treatment Systems (MTSs) and Natural Treatment Systems (NTSs) for Wastewater Treatment (WWT) and recycling approaches. Investigation on this trade-off is carried out using field data on Operation and Maintenance (O&M) costs and land requirements. It is then shown that none of them in solo are techno-economically viable and environmentally sustainable for WWT in urban areas in India. Hence, a paradigm shift in WWT in India is proposed to adopt Hybrid Treatment Systems (HTSs) approach. HTSs involve treatment considering a combination of natural and mechanized treatment approaches. Adoption of HTSs will result in energy savings and environmental benefits and hence will help India to achieve various national and international commitments of WWT and recycling.

Keywords: Wastewater treatment; Recycling; Natural treatment systems; Hybrid treatment;

Sustainability; India

1. Introduction

In India, there is a huge gap in domestic wastewater (sewage) generation and Wastewater Treatment (WWT), only 37% of the wastewater receives the treatment (ENVIS, 2019). Also, the installed capacity of many of the treatment plants have only primary treatment; for example, in Mumbai, only primary treatment exists for sewage of about 1600 Million Litres per Day (MLD) (Gupta et al., 2017). In the Ganga river basin similar situation exists. Industrial wastewater is another contributor to water pollution wherein WWT is responsibility of the generators.

Numerous WWT technologies are available, which can be mainly classified as Mechanized Treatment Systems (MTSs) and Natural Treatment Systems (NTSs) (Tare and Bose, 2009; Arcievala and Asolekar, 2013; Crites at al., 2014). MTSs (e.g. Activated Sludge Process, Sequencing Batch Reactor, Moving Bed Bioreactor, Membrane Bioreactor) are more commonly used for centralized treatment in cities as securing land for WWT is a great challenge and NTSs (e.g. Constructed Wetlands, Waste Stabilization Ponds, Duckweed Ponds) are more commonly used in rural areas (Kalbar et al., 2012a). Both the categories of treatment systems have advantages and disadvantages and are suitable for different settings (Kalbar et al., 2012a; 2012b). For example, MTSs are more energy intensive, however requires lesser land compared to NTSs.

Considering this gap in the treatment in India and progressive regulations, there is a need for installing new Sewage Treatment Plants (STPs) as well as augmentation of the old STPs to meet new regulations. In either case, the challenge for Indian cities will be to achieve cost-effective treatment. The capital expenditures usually can be arranged from several funding modes (Sethi, 2019), however the other constraints such as Operation and Maintenance (O&M) costs and land requirements limits the use of all variety of technologies available for WWT. Apart from these challenges, numerous issues are currently being faced in WWT, such as varied sources of Wastewater (WW), characterization of WW, emerging contaminants and their toxicity, emerging regulations, benchmarking performance, improving access to sanitation, and public perception about recycled sewage.

The challenges described above are not limited to India but are global (Villarín and Merel, 2020), and there are number of drivers for and against wastewater recycling (Kunz et al., 2016). Providing water and sanitation access sustainably to cities is a major global issue (Mahgoub et al., 2010). To overcome these challenges there is need for a paradigm shift in the WWT and recycling. Globally, various paradigm shifts are suggested to address these issues (Villarín and Merel, 2020). McCarty et al. (2011) proposed a Low Energy Mainline (LEM) as a strategy to promote wastewater recycling for irrigation as tremendous amount energy is consumed for aeration in biological treatment and precious nutrients are not recycled back to the food system in the conventional approach. Further, Batstone et al. (2015) carried out comparison of various platforms of nutrient and energy recovery and concluded that the LEM is potential approach for resource recovery in shorter term. Harder et al. (2020) highlights problems associated with linearized use of nutrients and globalization of nutrient flows and proposes reframing of human excreta management as part of food and farming systems to address unattended issues such as ensuring nutrient recovery. Source separation and on-site technologies of wastewater treatment and recycling is another proposed paradigm shift for sustainable WWT (Larsen et al., 2009); however, studies have shown that these systems may not always be better than the conventional approach on all aspects of sustainability (Thibodeau et al., 2011; Thibodeau et al., 2014) and hence there is a need for further assessment. Scale of implementation of the WWT is also an important factor and recently the focus has shifted to the scale and its relation to the energy intensity (Paul et al., 2019). Circular Economy in water sector is another framework that creates new avenues for the stakeholders to work together to give impetus to reuse and recycle wastewater (Kakwani and Kalbar, 2020). Finally, sustainability of the solutions should be of primary focus while implementing any solutions. The sustainability of treatment systems in this study is defined as the treatment which is feasible from all the dimensions of the sustainability i.e. economic, social and environmental (Kalbar et. al., 2016).

The above proposed paradigm shifts and emerging focus areas in WWT suggest a need to revisit the conventional approach of planning and implementation of WWT in India. The treatment gap in the wastewater generated and treated can be considered as an opportunity to plan for resource-efficient and sustainable water infrastructure in India. The present work focuses on bridging this need by proposing a new paradigm of Hybrid Treatment Systems (HTSs) by coupling mechanized and natural treatment systems (specifically CWs) and illustrates its usefulness in the context of current challenges faced for treatment of domestic wastewaters in India. The novelty of the work lies in the development of the HTS approach, which to the best of the author's knowledge is not currently being used for WWT. There have been studies which used hybrid treatment system terminology to the combination of mechanized treatments (Hai et al., 2007) or hybrid constructed wetlands (Vymazal, 2005); however, the proposal to use HTSs approach as a full-fledged strategy for achieving sustainable WWT is introduced for the first time in this work. The associated benefits of adopting the HTS approach in India for WWT are also discussed.

2. Progressive water regulations in India and its implications

The treatment of wastewater in India is stipulated by the discharge standards as shown in column A of Table 1, which are governed by the Schedule VI of the Environmental Protection Act of 1986 (EPA, 1986). In November 2015, these standards were proposed to be changed and more stringent standards were proposed by the Ministry of Environment, Forest & Climate Change (MoEF&CC), Government of India due to degraded water quality of water bodies in India (refer to column B of Table 1). However, later these proposed standards were relaxed by the MoEF&CC in October, 2017 (refer column C of Table 1). Finally, this matter was taken up in National Green Tribunal (NGT), an apex legal authority for environmental issues in India, which based on expert committee report dated 30th April, 2019 ordered more stringent discharge standards as shown in column D of Table 1 (NGT, 2019). The NGT has explicitly mentioned in the order that there cannot be different discharge standards for metro/urban areas and rural areas and these standards are applicable across India as well as also to the existing STPs. Out of the parameters listed in Table 1, the most important parameter in the current Indian context is Bio-chemical Oxygen Demand for 3 days at 27^{o} C (hereafter will be called only as BOD) and will be used as the representative parameter for discussing treatment efficiency in this study.

Table 1 Regulatory standard for discharge of treated wastewater in India (adapted from NGT, 2019)

Sr. No.	Parameters	Old Norms 1986	Draft Norms Nov. 15	MoEF&CC Notification Oct. 2017	NGT Order dtd. 30th April, 2019
		A	B	C	D
1	Biochemical oxygen demand (BOD) (3 days at 27ºC (mg/L)	<30	<10	<30 and <20 (metro and cities)	<10
2	Chemical oxygen demand (COD), mg/L, max	<250	<50	No limit	<50
3	Total Suspended solids (SS), mg/L, max	<100	<20	<100 and <50 (metro cities)	<20
4	Total Nitrogen (mg/L)	<100	<10	No limit	<10
5	Ammonical Nitrogen (mg/L)	<50	<5	No limit	No limit
6	Total Phosphorous	No limit	No limit	No limit	<1
7	Faecal Coliform (MPN/100 ml)	No limit	<100	<1000	<230

The new discharge standards have enormous implications on ground. Presently, 22,963 MLD of STPs are installed in India and there is a gap in the treatment of 38,791 MLD (ENVIS, 2019). First, the existing 22,963 MLD of STPs are need to be augmented to meet these new discharge standards. Secondly, the 38,791 MLD gap of sewage treatment needs to be planned to achieve these discharge standards. If India plans to fulfil this infrastructure gap, then there is a need for huge capital investment, land requirement, energy and O&M costs. Considering that secondary treatment level to be achieved for the currently generated sewage (i.e. BOD limit of 30 mg/L), the estimated capital investment for sewers and sewage treatment as per the year 2011 is INR 2,42,688 crore (about USD 35 billion) and almost same expenditure for O&M until the year 2031 (Ahluwalia et al., 2011).

The above investment will first help to improve the status of water quality and additionally, there are other national level benefits. For example, India is also committed to UN Sustainable Development Goals (SDGs) and the target for "Installed Sewage Treatment Capacity" under the SDG 6 (Clean Water and Sanitation) is 68.79% by 2030 (NITI, 2018). The targets for sewage treatment set under Atal Mission for Rejuvenation and Urban Transformation (AMRUT) and National Mission for Clean Ganga (NMCG) can also be achieved sooner. Additionally, the upgradation and installation of new STPs will provide an opportunity for implementing reuse, recycling and resource recovery strategies, which will help Indian cities to transit towards the Circular Economy and sustainable water infrastructure (Sgroi et al., 2018).

3. Trade-offs in the treatment approaches

WWT technologies vary in different characteristics such as energy consumption, land requirement, O&M needs, reliability (Tchobanoglous, et al., 1991; GRBMP, 2010; Arceivala and Asolekar, 2006). Choosing an appropriate technology is a multiple criteria decision-making problem (Kalbar et al., 2012a, 2012b). Various criteria representing environmental, economic and social dimensions need to be accounted in the decision–making process (Kalbar et al., 2016; Goffi et al., 2018; Ullah et al., 2020). However, currently in India only, BOD removal, capital costs, O&M costs and land requirement are used for technology selection.

As BOD to be removed is defined by the discharge standards, all the selected technologies have to meet the BOD removal target set by the regulations and/or Urban Local Body (ULB). Sewage in India has varied BOD (120-400 mg/L) range due to attributes such as water consumption, and density of population (CPHEEO, 2013; Singh et al., 2016; Singh and Kazmi, 2018). In this study, for evaluation of wastewater treatment systems an inlet BOD of 300 mg/L is considered and the effect of varying outlet BOD (ranging from 150 mg/L to 5 mg/L) from the treatment system on the O&M costs and land requirement is studied. Also, from the set of NTSs, horizontal sub-surface flow Constructed Wetlands (CWs) is selected as representative NTS for this study, which is one of the most widely applied NTS (Zhang et al., 2014).

Capital costs of the treatment systems do not vary significantly except for membrane based treatment system (GRBMP, 2010; Chauhan, 2017; Singh and Gupta, 2018). Also, capital costs of the WWT in India are arranged through various international funding agencies, central or state government funding schemes or through the partial funding from the ULBs (Ahluwalia et al., 2011; Sethi, 2019). Hence, if capital costs are not considered in the decision making, the choice of the technology mainly relies on O&M costs and land requirements.

In this study, data on O&M costs and land requirements for WWT systems are collated from number of studies focusing on Indian case studies (Sato et al., 2007; Tare and Bose, 2009; GRBMP, 2010; Kalbar et al., 2012a, 2012b; Chauhan, 2017; Singh and Kazmi, 2016; Singh and Gupta, 2018) and authors personnel communication with experienced practitioners. The annual O&M costs are expressed as Indian Rupees[1] per m^3 (INR/m^3) of treated wastewater and includes costs related with operational energy, manpower, chemicals, and, regular maintenance and repairs. The O&M costs of MTSs and CWs are shown in Fig. 1a.

The land requirement for horizontal sub-surface flow type CWs is dependent on the inlet BOD and target outlet BOD and can be estimated using Eq. 1 as given in Crites et al. (2014).

$$A_s = \frac{Q(\ln C_0 - \ln C_e)}{K_T.y.n} \qquad \text{Eq. 1}$$

Where,

A_s = wetland surface area (m^2)
Q = average design flow (m^3/d)

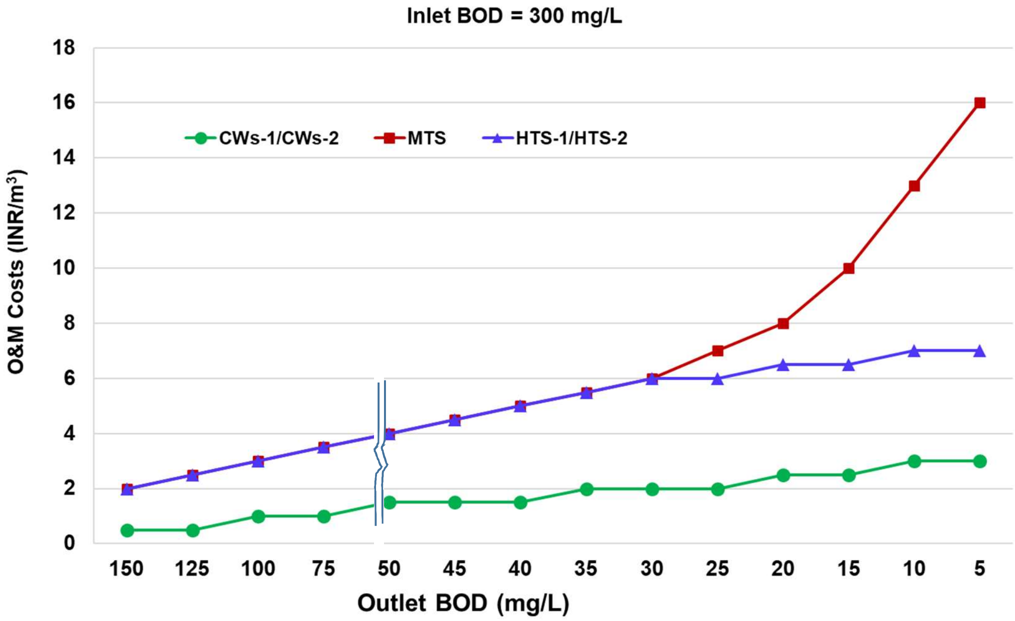
[1] 1 US Dollar = 71.2 Indian Rupees in December, 2019

C_0 = influent BOD concentration (mg/L)
C_e = effluent BOD concentration (mg/L)
K_T = rate constant = 1.1 d^{-1} at 20°C
y = design depth (m)
n = porosity of media

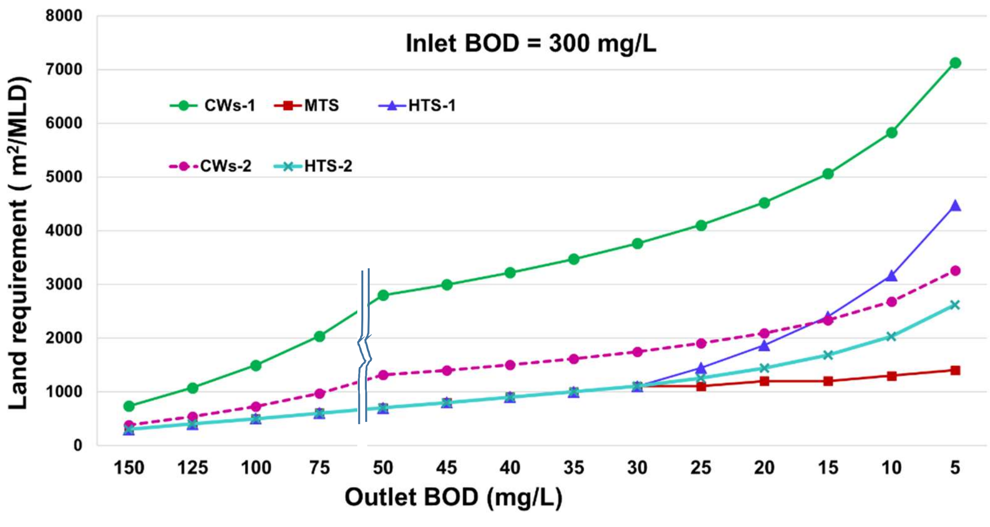
In this study, the average design flow of 1000 m^3/d is considered for the comparison, with depth of CWs bed as 0.9 m for shallow bed wetlands (hereafter referred as CWs-1) and 2 m for deep bed wetlands (hereafter referred as CWs-2), porosity of media considered is 30% and temperature as 30°C (temperature corrected K_T = 1.96 d^{-1}). A good primary treatment such as clarifier or sedimentation tank is considered (allocating 100 m^2 per MLD additional area) before the CWs assuming 30% removal of BOD (CPHEEO, 2013) and hence, the inlet BOD to the CWs beds is considered as 210 mg/L. For this inlet BOD and varying outlet BOD (ranging from 150 mg/L to 5 mg/L) land requirement as per the Eq. 1 is calculated for shallow bed wetlands and deep bed wetlands and is shown in Fig. 1(b). The land requirement estimated by this procedure is verified by the organic (BOD) loading rate (OLR) which falls within the acceptable range of 17.5 – 35 g BOD to be removed/m^2/day for warm climates for secondary level treatment (Arceivala and Asolekar, 2006).
As it can be seen from Fig. 1 (a), the O&M costs of MTSs increases linearly with the less BOD requirement at the outlet up to 30 mg/L. The rise in the costs is more steep (exponential) after the outlet BOD requirement reaches to 30 mg/L. This is evident as the removal of BOD further to 30 mg/L requires advanced treatment technologies, which pose additional burden on O&M costs. On the other hand, the O&M costs of CWs do not vary significantly with the BOD removal requirement, as this is a land-based treatment system and do not consume energy for operation.
The land requirements for MTSs and CWs are shown in Fig. 1(b). MTSs do not show significant variation in the land requirement until the outlet BOD reaches to 30 mg/L. Subsequently, there is a small stepwise rise in land requirement until outlet BOD of 5 mg/L. The land requirement for CWs exponentially increases with decrease in the outlet BOD value as there is direct exponential relationship between BOD to be removed and land requirement as governed by the Eq. 1. The typical land requirement for secondary treatment (BOD < 30 mg/L) using CWs is 3758 m^2/MLD for CWs-1 (shallow depth) and 1746 m^2 for CWs-2 (deep bed). Hence, CWs and other NTSs as secondary treatment are more feasible in rural and peri-urban settings (Kalbar et al., 2012a) or in urban setting with a decentralized approach (Sharma et al., 2010; Brunner et al., 2018). However, too small decentralized treatment systems may increase the financial costs and hence appropriate scale of implementation must be chosen to achieve optimal cost of the treatment (Tsagarakis, 2013; Yerri and Piratla, 2019).

4. Hybrid Treatment Systems (HTS)

The trade-off between the MTSs and CWs suggests that each of these systems are suitable for specific local conditions. A closer look at this trade-off in Fig. 1 reveals that MTSs can be coupled with CWs to achieve sustainable wastewater treatment and recycling in Indian cities. As MTSs require far less land compared to CWs and CWs require far less O&M costs compared to MTSs, for the secondary treatment, for outlet BOD requirement up to 30 mg/L MTSs can be used and for any further lower BOD removal requirement CWs can be used. This is feasible in Indian cities as the STPs are typically located at the outskirts of the city, and if planned from initially, an incremental land requirement can be allocated for any BOD removal lower than 30 mg/L using CWs. In this study, this approach of coupling MTSs with CWs is proposed to be called as "***Hybrid Treatment System***".



(a)



(b)

Fig. 1 O&M costs and land requirement for treatment approaches (MTS – Mechanized Treatment System; CWs-1 – Shallow Bed Constructed Wetlands; CWs-2 - Deep Bed Constructed Wetlands; HTS - Hybrid Treatment System)

The land requirement calculations for HTSs are based on the requirement of land for BOD removal from 300 mg/L to 30 mg/L considering use of MTSs. Then, the effluent from MTSs is to be applied to CWs beds and hence land requirement for BOD inlet of 30 mg/L and BOD outlet ranging from 25 to 5 mg/L is estimated as per Eq. 1. The MTSs land requirement and the incremental land requirement for additional BOD removal is then added to estimate HTSs land requirement for each level of BOD removal, which is shown in Fig. 1(b). Similarly, O&M costs for HTSs is calculated by combing MTSs and CWs costs and shown in Fig. 1(a).

Further, considering the trade-off in the land requirement and O&M costs two approaches of the HTSs are suggested and described in Table 2. As Fig. 1(b) indicates that land requirement for BOD removal up to 5 mg/L using HTS-1 approach tend to be significantly higher (about 4500 m^2 per MLD). Such a significant land area is difficult to be allocated for sewage treatment even in the periphery of the city considering large quantities of design flows. Hence, whenever the BOD removal requirement is about 5 mg/L deep bed wetlands can be used as HTS-2 approach (refer to Table 2), which will require about 2600 m^2 per MLD. Also, both types of CWs in have limitation in achieving BOD removal lower than 5 mg/L, as there will be always some residual background concentration (USEPA, 2000).

MTSs such as multi-media pressure filtration or membranes filtration can be adopted (additional 100 m^2 area can be considered for this) for BOD removal beyond 5 mg/L. The O&M costs of such a mechanized systems based tertiary treatment is significantly higher as these systems consumes significantly high energy and chemicals (Singh and Kazmi, 2016).

Table 2: Proposed Hybrid Treatment System Approaches*,# (MTS: Mechanized Treatment Systems; CWs: Constructed Wetlands)

HTS Approach		**Treatment System used For BOD removal up to 30 mg/L**	**Treatment System used For BOD removal up to 10 mg/L**	**Treatment System used For BOD removal up to 5 mg/L**	**Usefulness in Different Settings**
HTS -1		MTS	MTS + Shallow Bed CWs	MTS + Shallow Bed CWs	This approach is more suitable for rural and peri-urban setting both in centralized and decentralized manner where sufficient land is available. This approach can be used in cities as well where STPs are located at the outskirts of the city.
	Land requirement (m^2) per MLD	1100	3166	4469	
	O&M costs (INR/m^3)	6	7	7	
HTS -2		MTS	MTS + Deep Bed CWs	MTS + Deep Bed CWs	This approach is more suitable in peri-urban and urban setting both in centralized and decentralized manner where there is a land constraint.
	Land requirement (m^2) per MLD	1100	2029	2616	
	O&M costs (INR/m^3)	6	7	7	

*In rural, peri-urban or urban areas first attempts should be made to use CWs (or any other NTSs) directly after primary treatment, if this is not possible due to availability of land then only any suitable HTS approach should be adopted.

#For BOD removal requirement lower than 5 mg/L, tertiary treatment such as multimedia pressure filters / membrane filtration can be used after HTS-1 or HTS-2

5. Significance of HTS approach in achieving sustainable WWT in India

The results from Fig. 1 show that suitability of HTS is higher when the aim is to recycle the wastewater due to drastic savings in O&M costs as the incremental energy and chemicals required for achieving lower outlet BOD are avoided with use of the HTS approach. As it can be seen from Fig. 1(a) only after when outlet BOD requirement is lower than 30 mg/L, HTS approach becomes feasible. The additional land requirement for shallow bed CWs for BOD removal from 30 mg/L to 5 mg/L is 3369 m^2/MLD and from 20 mg/L to 5 mg/L is 2606 mg/L. If this size of land is not available, then deep bed wetlands can be adopted and depth of the wetlands (up to 2 m) can be chosen according the land availability as per Eq. 1. The same BOD removals are possible using MTSs by incremental area of 100 – 200 m^2/MLD, however, MTSs will require additional O&M costs of INR 14-16 per m^3 of treated wastewater.

Table 2 suggests that based on the available land at the planned STP location, decision can be taken about up to what level BOD to be removed using MTSs and then further BOD reduction can be achieved using shallow or deep CWs in a low cost and eco-efficient manner (as there is no energy requirement for operation of CWs). The aim in HTSs approach, however, should be to use land as much possible such that a sustainable wastewater treatment is possible. Decentralized infrastructure approach can be used to plan localized treatment such that use of NTSs can be encouraged (Parkinson and Tayler, 2003; Singh et al., 2015).

The use CWs enables sustainable wastewater treatment and recycling as it is not only useful for efficient organic load removal (80-90% removal) but also exhibits better nutrient removal efficiencies (40-50% for total nitrogen, 50-60% for total phosphorous) compared to energy intensive conventional MTSs (Vymazal, 2005; Lee et al., 2009; Vymazal, 2010). Additionally, Emerging Contaminants (ECs) such as pharmaceuticals and drugs, disinfectants, surfactants, pesticides are posing burden of treatment on sewage infrastructure globally as well as in India (Kalbar et al., 2018; Williams et al., 2019). CWs, which is a phytoremediation-based technology, has also a potential to remove ECs effectively (Langergraber et al., 2019).

Further, there is a global pressure to create eco-efficient water infrastructure and many counties are assessing environmental sustainability of water infrastructure to achieve SDG6 (Sørup et al., 2020). If the proposed HTS approach is implemented throughout India, there will be total annual energy saving (by considering avoided energy required for biological aeration for additional BOD removal lower than 30 mg/L) of about 200 GWh in the existing STPs and 340 GWh in the STPs that will be installed in near future to fill the gap in the treatment capacity. Additionally, this yearly energy saving will avoid annual total CO_2 emissions of about 0.45 Mt, considering India's current electricity grid mix. Additional carbon credits can be attributed to HTS approach for CO_2 fixed by the plants during the treatment (Kalbar et al., 2013). This will help India to create a sustainable water infrastructure and meeting the emerging challenges and progressive regulations such as BOD discharge standards of 10 mg/L. The HTS approach can easily be implemented in the 415 cities in India having population between 0.1 to 1 M with cumulative population of 216.4 M and in the 7417 towns (Census of India, 2011). For the 53 cities having population of million plus (Census of India, 2011), adoption of HTS approach is possible for the STPs located at the outskirts of the city or decentralized infrastructure approach can also be used. Such adoption of the HTS approach will help to achieve India's SDG 6 and SDG 11 targets sooner as well as sewage treatment targets set under the AMRUT and the NMCG, as the HTS approach is not only economical but also environmentally sustainable.

There are many other benefits than energy and CO_2 emission savings are possible by using the HTS approach. Different of NTS technologies can be used in HTS approach which can generate by-products such as biomass, nutrients, algal products, animal feed, fish feed, biodiesel (Shilton et al., 2012; Avellan et al., 2017). The study by Lekshmi et al. (2020) demonstrates how NTSs can be infused into social fabric of India and women empowerment can be possible in the circular economy framework. HTS can also be used of river and lake rejuvenations and it is already been used for Mansagar Lake rejuvenation in the Jaipur city (Asolekar et al., 2013). However, replication of such examples has not happened and hope this study will encourage the policy makers in India to adopt HTS as full-fledged strategy for creating sustainable WWT infrastructure in India.

The present work is limited to use BOD as the only parameter to assess the usefulness of the HTS approach in various settings and there is further need to assess the effectiveness of the HTS approach in the context of nutrient removal. There is need for future work on quantifying widespread social benefits of HTSs such as employment generation. Feasibility of HTS approach for industrial effluent treatment also need to be evaluated in future studies. The data used in this study is also limited and aggregated for entire India. The further studies can be initiated using the regional data and the applicability of HTS approach for each region can be assessed.

6. Conclusions

In India, tremendous amount of investment is needed to fill 73% gap in wastewater treatment infrastructure. Creating new infrastructure with low capital cost, low operational energy, low environmental footprint and minimum land requirement is the only path for Indian cities to accomplish various international and national commitments such as SDGs, AMRUT and NMCG. Also, the stringent progressive regulations and emerging contaminants in wastewater are posing newer challenges. The MTSs are not sustainable alternative to meet these challenges and NTSs are not feasible in Indian cities due to land constraints. Hence, in this study HTSs approach is proposed and shown that it's a more techno-economically feasible and environmentally sustainable alternative. The adoption of HTSs will save annual energy of about 540 GWh which will avoid around 0.45 Mt of CO_2 emissions compared to MTSs. The study provides details of various approaches of HTSs and its usefulness for various settings in India. Further work is needed to explore the potential of remaining NTS technologies such as duckweed ponds, waste stabilization ponds in HTS approach and their suitability in India and other countries.

HTSs becomes more applicable when the objective is to recycle wastewater, as the WWT requiring outlet BOD lower than 30 mg/L can be achieved through CWs (or any other NTSs) by low O&M costs and moderate land requirement. If planned in advance, the additional land requirement can be secured by the ULBs for leveraging on HTSs both in the centralized and decentralized infrastructure approach. The results of this study demonstrated a need for a paradigm shift in WWT in India and it is hoped that practitioners, ULBs and policy makers will adopt the HTS approach as a strategy for achieving sustainable WWT.

Declarations: Not applicable

Funding: The work received funding to the author by the Department of Science and Technology, Government of India through the projects "Innovation Centre for Eco-prudent Wastewater Solutions (IC-EcoWS)" project number DST/TM/ WTI/WIC/2K17/83(G) and "Fast Forward to SDG6: Acceptable and Affordable Water in Secondary Indian Cities (4WARD)" project number DST/TM/EWO/WTI/2K19/UWS-03(C4).

Acknowledgement: Author is thankful to the Editor and anonymous reviewers for their constructive comments. Author also thank Ms. Nikita Kakwani for proof reading the manuscript.

Conflicts of interest/Competing interests: Not applicable

Availability of data and material: Not applicable

Code availability: Not applicable

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