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Sustainability Study of In-situ Hydroponic Vetiver System for Urban Wastewater Management in Developing Countries: A Theoretical Review

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Abstract: Urban wastewater management is a crucial challenge in the small and medium towns situated in the developing countries worldwide. These towns are also facing an increasing gap between infrastructure and population growth. A conventional approach to curb these problems is the application of cost-intensive electro-mechanical sewerage technologies, as adopted in developed countries. The first part of this paper derives a set of indicators to framework a sustainable urban wastewater treatment system by reviewing the current state of wastewater management in developing countries, for example, the sample case study being India. The second part evaluates the potential performance of the proposed alternative in-situ hydroponic vetiver system (HVS) against those set of sustainability indicators by reviewing the worldwide performance of the HVS. The objective of this paper is to assess the potential viability of the HVS as a sustainable and cost-effective alternative for developing countries. The current analysis can aid in mainstreaming the use of HVS in policy making and urban planning.

Key words: Phytoremediation, hydroponic, vetiver, decentralised, low-cost wastewater treatment, India.

Introduction

The world is rapidly urbanising, up from 30% in 1950 to 54% in 2014, higher urbanisation can be seen in developed countries. Some continents such as Africa, Asia, and Latin America accounted for more than 90% of global urban growth, indicating a faster rate of urbanisation. Among these, the rate of urbanisation was observed to be the fastest in the small and medium towns of Asia and Africa, having less than 1 million population. It is projected that by 2050, the share of the urban population in developing countries will reach 63.4%, which is close to the global average of 66.4% (UNDP, 2016).

With rising urbanisation, wastewater generation is becoming unmanageable, much to the helplessness of the municipal bodies worldwide, especially in small and medium towns of developing countries. Globally, over 80% of wastewater is released in the environment without adequate treatment into existing water bodies while a minor part percolates underground (UN-Water, 2015). Hence, any wastewater management system needs to ensure suitable treatment along with disposal within the prescribed safety standards for disposal.

Aims and Scope of the Study

This paper aims to do a theoretical sustainability study of in-situ hydroponic vetiver system (HVS) as

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a potential system for urban wastewater management in developing countries, especially small and medium towns, with emphasis on the Indian context, based on literature review evidence.

Approach to Study

The first objective is to deconstruct the existing conventional approach to wastewater management into a set of sustainable indicators by reviewing the wastewater scenario globally and in India.

The second objective is to theoretically reconstruct the proposed application of the in-situ HVS against the derived indicators to assess sustainability by reviewing worldwide applications of the HVS.

Global and Indian Wastewater Treatment Context

Global Wastewater Scenario

The wastewater treatment and disposal varied regionally depending on income levels and climate of the country (Sato et al., 2013; UNWWAP, 2017), as elaborated below:

1. On average, wastewater treatment for high-income, upper-middle-income, lower-middle-income, and low-income countries was 70%, 38%, 28%, and 8%, respectively.
2. Due to the gross unavailability of data in the developing and underdeveloped countries, it cannot be assumed that wastewater collection is equivalent to wastewater treatment, common reasons being lack of treatment plant, poor operation and maintenance (O&M) of the treatment plant or overflow during storm events.

Indian Wastewater Scenario

The most significant component of pollution in water bodies in India is from urban domestic wastewater disposal (CPCB, 2019) as illustrated in Table 1 below.

Table 1: Wastewater generation and treatment capacities in India in millions of litres per day (MLD)

Item	*Year 2001*	*Year 2009*	*Year 2015*
Wastewater generated (MLD)	29,129	38,255	61,754
Wastewater treatment capacity (MLD)	6,190	11,788	22,963
Missing capacity (MLD)	22,939	26,467	38,971
Treated wastewater (%)	21	31	37
Untreated wastewater (%)	79	69	63

Source: CPCB, 2019; ENVIS Centre on Hygiene Sanitation Sewage Treatment Systems and Technology, 2019; Planning Commission Working Group, 2011.

Table 1 shows that while wastewater generation increased only by 31% between 2001 and 2009, it recorded an increase of 61% between 2009 and 2015. Meanwhile, wastewater treatment capacity increased by 61% between 2001 and 2009 whereas it only increased by 47% between 2009 and 2015. This indicates that the wastewater treatment infrastructure was failing to keep pace with the requirement in the urban areas of India.

Further analysis (Planning Commission Working Group, 2011), as summarised in Table 2 below, revealed that Class-I cities (population between 0.1 and 1 million) had a backlog of 68% untreated wastewater while for Class-II cities (population between 50,000 and 99,999) it was 92%. The reason for such stark difference could be the wide mismatch between the overall government fund allotment of Class-I and Class-II cities which was based on the town population.

Table 2: Comparative wastewater treatment capacity in Millions of Litres per Day (MLD)

Item	*Class I (0.1 – 1 million)*	*Class II (50,000 – 99,999)*	*Total*
Waste water generated (MLD)	35,558	2,697	38,255
Wastewater Treatment capacity (MLD)	11,554	234	11,788
Missing Capacity (MLD)	24,004	2,463	26,467
Untreated Wastewater (%)	68	92	70

Source: Planning Commission Working Group, 2011.

Centre for Science and Environment (CSE) report stated that the actual installed treatment capacity in India was only 19% of the total sewage generation. Further, this limited capacity was reportedly operational for up to 72% utilisation (Srinivasan and Suresh Babu, 2008). A sample survey (Sinha and Nazimuddin, 2008) of existing sewage treatment plants (STPs) classified the performance of only 10% as ‘good’ and 54% as ‘poor’ and ‘very poor’ (Hingorani, 2011). It is an indirect indication that even the existing systems in India were under performing.

Constituents of Urban Wastewater

UN-Water (2015) observed the following classifications for understanding wastewater:

1. Depending on the source of wastewater, a broad definition could be "a combination of:
   - domestic effluent consisting of blackwater (excreta, urine, and faecal sludge) and greywater (kitchen and bathing wastewater);
   - water from commercial establishments and institutions including hospitals,
   - industrial effluent, stormwater, and other urban run-offs;
   - agricultural, horticultural, and aquaculture effluent, either dissolved or as suspended matter" (Corcoran et al., 2010).
2. Further, Henze and Comeau (2008) added that there are seven categories of wastewater generated in urban areas such as domestic, institutions, industrial, sewer infiltration, stormwater, leachate, and septic tank wastewater.
3. Depending on the constituent composition, wastewater contains several pollutants and contaminants including:
   - plant nutrients (nitrogen, phosphorus, potassium);
   - pathogenic microorganisms (viruses, bacteria, protozoa, and helminths);
   - heavy metals (cadmium, chromium, copper, mercury, nickel, lead, and zinc);
   - organic pollutants (polychlorinated biphenyls, polyaromatic hydrocarbons, pesticides);
   - biodegradable organics (BOD, COD);
   - micro-pollutants (medicines, cosmetics, cleaning agents).
4. Depending on volume composition, wastewater is approximately accepted to be 99% water and 1% suspended, colloidal, and dissolved solids, with marginal variation in components depending on the source.

In India, the term sewage means all household wastewater, which is a mixture of all the above.

Existing Framework and Classification of Wastewater Management Systems

The technical framework of any wastewater management system could be stagewise divided into collection, transportation, treatment, and disposal. Veenstra et al. (1997) further categorised wastewater management systems into on-site and off-site systems as elaborated below:

- On-site systems involve the collection of domestic wastewater from households either through stand-alone systems such as soak pits or septic tanks. They are most predominant in small and medium towns of developing countries due to the absence of sewer networks.
- Off-site systems comprise of city-wide sewer network and sewage treatment plant (STP) forming the sewerage system for collection, transportation and treatment of wastewater. In most developing countries, a common drain transports both the sewage and drainage usually due to lack of funds and availability of space (CPHEEO, 2013).

Derivation of Sustainability Indicators

Challenges of Conventional Sewerage Systems

Conventional sewerage systems have been the default technical choice for ULBs worldwide with variations only in technology. However, some practical issues emerge in implementing and managing them in the Indian context, as analyzed below (CPHEEO, 2013):

1. City-wide sewer laying requires pipe purchase, excavation and rebuilding roads involving substantial capital investment.
2. Streets are usually narrow and meandering in slums/fringe areas of organically developed towns. Deep excavation for pipe-laying can destabilise the foundations of surrounding buildings and is not conducive. Pipe-laying in meandering streets requires an increased number of joints to negotiate the curves, rendering the system technically and financially inefficient.
3. Sewage is transported by gravity in reclining sewer pipes which is raised after certain intervals by lifting stations (LS) and pumping stations (PS) till it reaches the STP, involving significant capital investment and O&M costs.
4. The location of STP/STPs requires to be simultaneously close to the outfall as well as be the converging point of the city-wide sewer network. Such vacant land might be expensive or completely unavailable in an already built-up town. Additional capital investment is required for STP construction.
5. O&M of STPs is high because of power consumption for running electro-mechanical processes, regular chemical dosage, and skilled workforce (Shah, 2016).

6. Existing sewer networks, lacking proper maintenance, are often broken or illegally tampered by local communities leading to loss en route, causing environmental pollution (UNWWAP, 2017).
7. Cities having sewer networks do not have treatment plants. Survey by Central Pollution Control Board in 2011 showed that only 2% of towns in India have both sewer networks and STPs (Shah and Kulkarni, 2015).

Conventional sewerage systems are absent in most cities because of the above reasons. Ahluwalia (2011) estimated that the projected cost of water supply and sewage treatment in India would be approximately USD 805 billion over the next 20 years (Shah and Kulkarni, 2015) employing conventional technologies.

Shah and Kulkarni (2015) further argued that decentralised wastewater management can service unserved areas, minimise the pressure of transporting to a single location, reduce land requirement, reduce treatment and O&M costs. The Planning Commission Working Group (2011) suggested that the guiding principle is to cut the sewerage construction cost by minimising sewer network and treating waste as a resource for reuse. They also proposed the treatment of sewage in open drains using alternative biological methods. Hence, it is imperative to adopt alternative, cost-effective, low maintenance, and sustainable wastewater management systems.

Mapping the Sustainability Indicators of an Urban Wastewater Management System

As evident from the previous section, the following issues, in the context of small and medium towns of developing countries, are omitted from the discussion because:

1. Presently, as most of the STPs are either absent or underperforming, the technological efficiency of the STPs is not discussed.
2. Selective treatment options are not possible as existing canals receive a non-segregated discharge of domestic and industrial wastewater from point/non-point sources.
3. As existing sewerage systems are technically and financially unsustainable, the policy interventions to strengthen them are not discussed.

Hence, based on the above arguments, challenges, and gaps identified, an effective sustainable wastewater management system may be evaluated by the following overarching indicators:

1. Higher collection and transportation efficiency
2. Higher treatment and disposal efficiency
3. Higher use of existing infrastructure
4. Lesser dependence on land location and land area
5. Lower capital investment
6. Lower O&M cost
7. Lower energy input
8. Higher recycling potential
9. Higher ease of implementation
10. Higher aesthetic appeal.

Comparing the In-situ Hydroponic Vetiver System (HVS) for Sustainability

Concept of Phytoremediation and HVS

Phytoremediation is a naturally occurring process recognized and documented by humans more than 300 years ago (Paz-Alberto and Sigua, 2013). It has gained prominence in the last four decades. Phytoremediation can be summarised as a set of eco-friendly technologies based on plants (aquatic, semi-aquatic and terrestrial), associated enzymes and microorganisms enabling water consumption and uptake, removal, retainment, transformation, degradation or immobilisation of contamination (organic and/or inorganic) from soil, wastewater and atmosphere (Farraji, 2014).

Ponds and wetlands are widely accepted urban wastewater treatment systems, an upcoming variant of floating treatment wetland (FTW). It consists of hydroponically growing emergent wetland plants on floating structures, thereby improving the treatment performance of conventional ponds without being constrained by the requirement of shallow water depth (Headley and Tanner, 2008). FTWs include emergent plants such as rushes, reeds and sedges, however, they do not include aquatic plants that form a free-floating thin layer on the water surface (e.g., duckweed, azolla, etc.) or plants having buoyant leaf bases (e.g. water hyacinth, water lettuce, Salvinia, etc.) (Headley and Tanner, 2008).

Among emergent wetland plants, vetiver grass (VG) is unique in totality as a phytoremediating plant under hydroponic conditions and has been extensively been researched on various polluted wastewater, especially *Vetiveria zizanioides* reclassified as *Chrysopogon zizanioides* (Truong et al., 2007). The growth of the roots and shoots of the VG in HVS indicate healthy nutrient removal. Worldwide research on HVS has been mostly on stagnant water bodies, lakes, wetlands, or laboratory conditions having high hydraulic retention time (HRT), which allows greater absorption by the dense root systems, thereby increasing efficiency. There is scope for future research on measuring the performance of HVS in flowing water.

HVS was reportedly used as phytoremediation for batik production wastewater (Effendi et al., 2018), tapioca factory organic wastewater (Indrayatie et al., 2013), phenol degradation in illegally dumped industrial wastewater (Phenrat et al., 2017), tetracycline waste (Datta et al., 2013), organic waste (Chua et al., 2012), fish farming wastewater (Effendi et al., 2015), crude oil-contaminated water and tofu production wastewater (Seroja et al., 2018).

HVS demonstrated survival rates ranging from 75 to 100% even after 8 weeks in wastewater (Boonsong et al., 2018). A study on industrial wastewater purification showed progressive shoot height growth in HVS (Otieno et al., 2018; Yeboah et al., 2015). VG was tolerant when submerged beyond 120 days, surviving partial submergence up to 8 months in Venezuela and around 3 months in a muddy water trial in Cambodia (Danh, 2015).

Research infers that VG is a potential on-site treatment system for removing nutrients and organics from domestic and industrial wastewater (Darajeh et al., 2014; Roongtanakiat et al., 2007; Worku et al., 2018) raising increasing interest among commercial and scientific community as a recommendation for decentralized wastewater treatment and reuse (Lopez-Chuken, 2012; Worku et al., 2018).

Mapping the Sustainability of an Integrated In-situ HVS

As per the above conclusions, a city-wide in-situ HVS on existing canals is proposed as an integrated collection, transportation, treatment, and disposal system. Following is a comparison of sustainability observed in-situ HVS with conventional sewerage systems based on the 10 identified indicators.

1. **Collection and transportation efficiency** is higher as the existing canals are utilised.
2. **Treatment and disposal efficiency** is higher being on-site and integrated with the collection and transportation of wastewater.
3. **The use of existing infrastructure** is higher as the system involves floating the plant platforms directly on existing canals.
4. **Lesser dependence on land location and land area:** Utilisation of existing canals bypasses the land requirement for STPs or its dependence on location. Additional treatment, if required, can be done in water bodies in fringe areas at a cheaper cost which can also be aesthetically maintained for citizen use.
5. **Capital investment requirements** comprise mainly of plant purchase and floating garden installation, which is negligible compared to sewerage systems.
6. **Operation and maintenance cost** is low as it comprises of occasional shoot trimming or replacing dead plants if any.
7. **Energy footprint:** HVS, being an entirely naturally run biological system, require no additional energy input. To enhance the oxidation of wastewater, solar-powered aerators may be installed in-situ.
8. **Recycling potential** is high as VG shoots/entire plants can be reused as good cattle fodder, handicrafts, roof thatch, mud-brick making, strings, ropes, ornaments, oil extraction, etc. (Truong et al., 2007). Thus, VG has the potential to economically cater the weaker sections of local community if a revenue model is instituted.
9. **Ease of implementation** is high as installation requires low skill workers/gardeners/labourers readily available in developing countries alongwith expert supervision during implementation.
10. **The aesthetic appeal** of canals and adjoining banks is enhanced by transforming them into floating gardens.

All these attributes favourably increase the potential for rapid installation, replication and scalability of HVS.

Discussion

The potential positives of in-situ HVS are highlighted in the previous section. The following are some foreseeable challenges in the successful implementation of this system in developing countries.

1. Existing research has assessed HVS in isolated contexts on a technical experimental scale but not on a city-wide scale, which may introduce its own complex socio-economic and governance challenges.
2. Wastewater canals are usually inaccessible/silted up/blocked/garbage covered, which may adversely impact the performance of HVS.
3. HVS needs to be installed strategically in canals so as not to interfere with the navigation of small boats and ferries.
4. An effective context-specific stewardship model needs to be developed that discourages premature shoot cutting by local people for reuse.

Future research is needed to ascertain the exact level of required deployment (amount, frequency, distance, etc.) for HVS to meet the desired water quality standards in a real-world urban setting.

Conclusion

This paper analysed the performance of existing urban wastewater management systems in small and medium towns of developing countries including India by reviewing global and Indian reports. The analysis revealed gaps that were mapped into 10 indicators of sustainability for any urban wastewater management system in developing countries. Existing research on the performance of vetiver grass under hydroponic conditions as a phytoremediation plant was further studied. From these two review studies, the authors theoretically mapped an in-situ hydroponic vetiver system against the sustainability indicators and concluded that this urban wastewater management system is technically, financially and environmentally sustainable. Observations and inferences of this paper can influence policymakers to rethink the urban wastewater management strategy and adopt the in-situ HVS as a sustainable approach.

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