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Evaluating wastewater treatment infrastructure systems based on UN Sustainable Development Goals and targets

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ABSTRACT

A multi-criteria comparison of algal-based and activated sludge-based wastewater infrastructure systems based on 30 process parameters derived from the UN Sustainable Development Goals (SDGs) is presented to assess their environmental, economic, social, and overall sustainability. The classical high-rate algal ponds (HRAP) and an emerging mixotrophic algal system (A-WWT) were selected as algal-based systems; and the conventional activated sludge (CAS) system and the membrane bioreactor (MBR) system, as activated sludge-based systems. Visual PROMETHEE outranking software was adopted to determine the preference scores and ranking of the four systems under twelve distinct scenarios/priorities. The mixotrophic A-WWT emerged as the preferred technology in environmental, economic, and overall sustainability aspects resulting in net positive preference scores (0.40, 0.53, and 0.36, respectively). The MBR system outperformed all the other technologies from the social sustainability perspective due to its lower footprint and better-quality effluent including significant pathogen removal. Even though HRAP was preferred over the CAS system in the context of environmental sustainability (preference scores of −0.22 in HRAP vs −0.27 in CAS), preference scores for them were similar in the context of economic sustainability (−0.33 for HRAP and CAS), and lower from social (−0.14 in CAS vs −0.67 in HRAP) and overall sustainability (−0.22 in CAS vs −0.34 in HRAP) perspectives. Scenario-based assessments indicated that preference ranking is strongly dependent on the decision maker's priorities. Good agreement between the findings from this study with literature reports adds credence to the validity of the proposed process parameters. Parameters and the method proposed herein could be useful in evaluating wastewater treatment technologies from a sustainability perspective.

1. Introduction

Globally, urban population has increased from 30% in 1950 to 55% in 2018. It has now been projected that by 2050, 68% of the world's population will be concentrated in urban cities (United Nations, 2019a), most of which do not even exist today. Even though urban cities across the world are estimated to occupy only a fraction of the land area (~5%), their population density accounts for 70% of the energy use and contributes to the generation of 70% of global warming gases (Pickett et al., 2019), Foreseeing the imminent negative consequences of the projected urbanization, member countries of the United Nations have unanimously agreed on an agenda— the 2030 Agenda for Sustainable Development and for the well-being of the planet and its inhabitants (United Nations, 2018). This agenda comprises 17 Sustainable Development Goals (SDGs) with a total of 169 targets to be achieved by 2030 (Table A1 in the Appendix). Among the 17 SDGs, SDG #11 which aims to "make cities and human settlements inclusive, safe, resilient, and sustainable" and SDG #6, which aims to "ensure availability and sustainable management of water and sanitation for all" (United Nations, 2020) are directly impacted by rapid urbanization (Delanka-Pedige et al., 2021).

A pathway towards sustainable urbanization can be guided by the social, economic, and environmental pillars of sustainability

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(United Nations, 2019a). A prerequisite for planned urbanization is the deployment of sustainable infrastructure to ensure economic and social welfare of the inhabitants without harming the environment (Adshead et al., 2019). Currently, investments are neither adequate nor sustainable to fulfill infrastructure gaps, particularly in developing and under-developed demographics; investments needed to ensure sustainable infrastructures to meet the 2030 Agenda have been estimated to be around $90 billion (Bhattacharya et al., 2015). As a solution, Alcamo (2019) has pointed out the possibility of implementing combined actions for mutually benefiting SDGs and their targets. Following that notion, previous reports have pointed out the linkages/interdependencies of SDG #6 (Delanka-Pedige et al., 2020b) with other SDGs including SDG # 11 (Delanka-Pedige et al., 2021) in the context of the wastewater infrastructure, which is a basic and critical component of the urban infrastructure. Fig. 1 summarizes the linkages and interdependencies among the SDGs and their targets with sustainable wastewater infrastructure.

Historically, the primary goal of the wastewater infrastructure has been to provide sanitation and protect the ecosystem through collection and end-of-pipe treatment of wastewater to meet the discharge standards. In the context of the 2030 Agenda, the traditional wastewater infrastructure falls short in meeting many of the SDGs (Zhang et al., 2019). In an assessment of the global progress towards meeting the targets of SDG #6, United Nations Water concluded that, at the rate of development in 2018, the world will not be able to meet the targets of SDG #6 by 2030 (United Nations, 2019b). It has been suggested that affordable and sustainable wastewater infrastructure systems will have to be developed for deployment in rapidly growing cities and for replacement of the obsolete infrastructure in developed countries.

Typically, selection of appropriate technologies for the wastewater infrastructure has been based solely on economic and environmental considerations with little regard for social aspects (Abyar et al., 2020). Although a few have considered all three sustainability concerns in their evaluations (Muga and Mihelcic, 2008), none have explicitly aligned their evaluations with the 17 SDGs and the 169 targets (Vidal et al., 2019). As such, in the first part of this study, measurable indicators/parameters directly related to the SDGs and their targets were derived for use in assessing alternate technologies for the wastewater infrastructure.

The second part of this study illustrates the application of a multi-criteria decision making (MCDM) approach to assess emerging wastewater technologies against the well-established ones in the context of SDGs for adoption in sustainable wastewater infrastructure. The intent here is not to rank the technologies *per se*; rather, to demonstrate the use of MCDM approach in identifying areas for refinement/improvement of the emerging technologies as well as established ones towards meeting the SDGs. Although different technologies have their own merits and demerits in contributing towards the SDGs and their targets, the MCDM approach normalizes them on a quantitative scale for assessing their sustainability based on multiple criteria.

One of our previous papers illustrated the use of MCDM approach in ranking 5 sewage treatment processes on the basis of 11 quantitative and 4 qualitative criteria (Munasinghe-Arachchige et al., 2020). Another one of our MCDM studies evaluated the potential of an emergent algal wastewater treatment (A-WWT) system in meeting targets set specifically for SDG #6 (Delanka-Pedige et al., 2020b). In another related paper, we reported on 5 attributes of wastewater systems related to the SDGs and derived 36 process parameters to quantify the 5 attributes for comparing the A-WWT

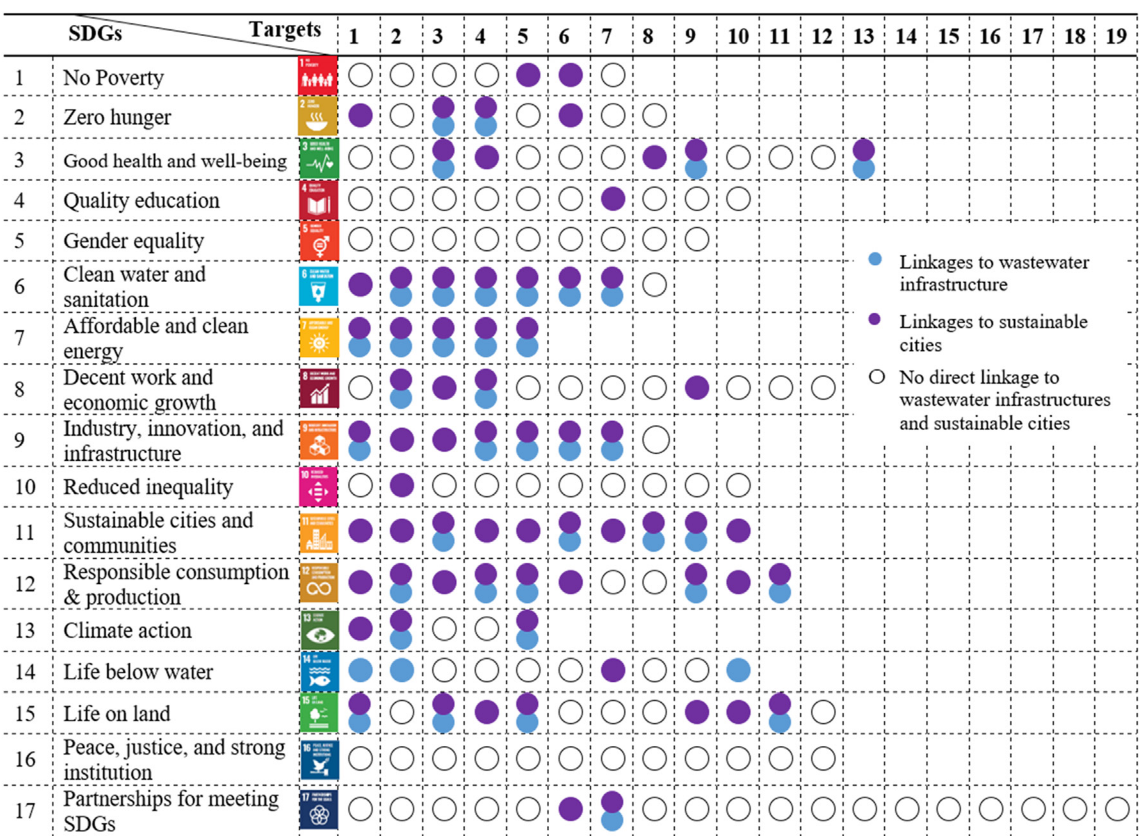

Fig. 1. Interdependencies of wastewater infrastructures, sustainable cities, and other SDGs.

system with the conventional activated sludge system in meeting SDG # 11 (Delanka-Pedige et al., 2021). In the current study, we build upon the above efforts to assess two algal-based and two activated-sludge based wastewater systems for their suitability for serving as sustainable wastewater infrastructure. Towards this end, 7 attributes of wastewater infrastructures are proposed here, which are quantified by 30 indicators/measures aligned with the 17 SDGs and their targets; together, these indicators/measures span the social, economic, and environmental sustainability dimensions of wastewater infrastructure.

Since sustainability-based selection of wastewater infrastructures will not necessarily assure the long-term existence and continuous and stable operation, it is important to incorporate priorities/potentials and limitations of individual nation/region/decision-maker in the process of selecting the most preferable treatment option. For instance, even if some of the high-tech wastewater infrastructures enable resources recovery (energy, nutrients, high-quality effluents) to improve sustainability, they may not be affordable for under-developed nations (Oladoja, 2017); and even if they were affordable by certain developing countries, lack of adequate operation and maintenance contribute to frequent failures of systems jeopardizing the people and environment (Starkl et al., 2013). In contrast, in the case of developed countries, despite the financial and technological potentials, some of the novel green technologies might not be appropriate due to limitation of resources (e.g: land) (Stefanakis, 2019). As such, in the third part, the MCDM approach is applied to illustrate the importance of decision maker's priorities in selecting appropriate wastewater infrastructure under 12 different scenarios. Additionally, this study also examined the sensitivity of the MCDM approach to the measures of the criteria used in the analysis.

2. Materials & methods

2.1. SDG-related indicators/measures for evaluating wastewater infrastructure

As illustrated in Fig. 1, wastewater infrastructures and the 17 SDGs are interconnected explicitly or inferentially. To quantify the degree of contribution of different wastewater technologies towards SDGs, and eventually towards sustainable cities, we have identified seven attributes relating to challenges (negative aspects) and opportunities (positive aspects) associated with wastewater infrastructure: 1) effluent quality, 2) pathogen removal, 3) energy consumption, 4) gaseous emissions 5) nutrients recovery, 6) footprint, and 7) reliability. Then, the above opportunities and challenges are mapped to appropriate SDGs and their targets to derive the following 30 sustainability indicators/measures ($P_1 - P_{30}$ in Table 1). Several of these indicators/measures are routinely measured in all wastewater treatment systems; others can be readily quantified in terms of available data.

2.2. Data collection and calculations

In this study, two algal-based and two activated sludge-based wastewater treatment technologies were selected as example for evaluation. The two activated sludge-based systems are the conventional activated sludge (CAS) system and the membrane biological reactor (MBR) system. The two algal-based systems are the classical high-rate algal ponds (HRAP) and an emergent mixotrophic algal wastewater treatment (A-WWT) system. It is acknowledged that these four technologies differ in their attributes and in the extent of their contributions to the SDG goals/targets, making direct comparisons using traditional measures/methods questionable. Since all four technologies can provide the minimum level of treatment to meet secondary discharge standards, the intent of the MCDM assessment here is to illustrate how those technologies could be enhanced/refined towards meeting the SDGs.

Parameter values of the CAS system were collected from a previous study which considered aerobic oxidation and nitrification followed by gravity separation of biosolids in a secondary sedimentation tank (Munasinghe-Arachchige et al., 2020). Parameters of the MBR system were extracted from a study that included aerobic oxidation, improved phosphorus removal via aluminum sulfate, nitrification, and denitrification (Bertanza et al., 2017); operating conditions of the actual MBR system was extracted from elsewhere (Judd, 2010). Operating parameters reported by Craggs et al. (2012) and resources recovery data reported by Munasinghe-Arachchige et al. (2020) were used to assess the HRAP process. Process parameters of the emergent A-WWT system were obtained from previous reports on fed-batch operation (Delanka-Pedige et al., 2020; Tchinda et al., 2019); pathogen removal (Delanka-Pedige et al., 2020); resources recovery (Abeysiriwardana-Arachchige et al., 2020; Munasinghe-Arachchige et al., 2021); and MCDM evaluation and process intensification (Munasinghe-Arachchige et al., 2020).

In cases where data were not readily available, estimates were based on stoichiometry (detailed in Appendix A) or from other literature sources. To minimize disparities among the selected treatment processes, values for most of the process parameters were reported using the functional unit of 1 m^3 of wastewater flowing through the treatment. In all four processes, it was assumed that the generated activated sludge/algal biomass is anaerobically digested to produced gaseous methane used as a biofuel. The residual sludge is assumed to be used as fertilizer after drying while the digester supernatant is recycled to the headworks. Completed evaluation matrix containing 30 process parameters for the four sewage treatment alternatives is included in Table 2. Salient features of each treatment process and calculations are detailed in Appendix A.

2.3. Multi-criteria evaluation of sustainability

Continuing our previous studies, we have selected the PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) method in the current study as well. PROMETHEE is a widely used outranking method which uses a pairwise comparison of alternatives for each of the process parameter (criterion) (Vinodh and Girubha, 2012). The Academic version of the Visual PROMETHEE software package was adopted here following the procedures (Munasinghe-Arachchige et al., 2020) and theories (Vinodh and Girubha, 2012) detailed previously. Even though the Visual PROMETHEE software package offers six different built-in preference functions, the "usual" function was applied for all the selected process parameters to avoid complexities.

In PROMETHEE, positive (suitability of a particular alternative over other alternatives), negative (suitability of other alternatives over a particular alternative), and net (overall suitability) outranking flows are calculated for all pairs of the four alternatives to rank them sequentially from most preferred to least preferred (Vinodh and Girubha, 2012). Preference directions (min/max) applied for all the process parameters are given in Table 2. Assigning accurate weights to each of the process parameters is a sensitive task and based on the decision maker's priorities and preferences, infinite outcomes are possible (Kalbar et al., 2013). In the context of this study, the assessment was conducted assigning an equal weight of 1.0 to all of the process parameters considered.

2.4. Sustainability-based and scenario-based assessment

To accommodate the decision maker's priorities that can influence the ranking of the alternatives, we performed two types of

Table 1
Derivation of process parameters to evaluate sustainability of wastewater treatment technologies.

Attributes of wastewater infrastructure	Opportunities	Challenges	Linkages to SDG targets	Process parameters considered
Effluent quality	Potential for reuse high-quality effluent for potable and non-potable applications; combat water scarcity; improve resource use efficiency and conserve ecology	Poor quality effluent can contaminate surface waters, promote eutrophication, degrade soil quality; aggravate water scarcity; additional cost for effluent treatment, and ecological impact mitigation.	2.3, 2.4	P1: Effluent BOD
			3.3, 3.9	P2: Effluent NH_4–N
			6.1, 6.3, 6.4, 6.6	P3: Effluent PO_4
			9.1, 9.4	P4: Effluent COD
			11.3, 11.6, 11.9	P5: Effluent TN
			12.4	P6: Effluent TP
			14.1, 14.3	
			15.1, 15.3	
			17.7	
Pathogen control	Pathogen free effluents are safe for reuse; reduced disinfectant demand and lower possibilities of subsequent disinfection by-products (DBP) formation	Health and safety issues due to pathogen outbreak; higher disinfection demand and DBP formation; increased health risk in water reuse; transmission of antibiotic resistance.	3.3, 3.9	P7: LRV of *E. coli*
			9.1	P8: LRV of Fecal coliform
			11.5, 11.9	P9: LRV of Somatic coliphages
			12.4	P10: LRV of F-specific coliphages
				P11: LRV of ARBs
Energy demand	Low energy consumption and energy-efficient treatment can conserve fossil- fuel reserves; reduction in operation and maintenance costs; reduction in indirect emission of greenhouse gases (GHGs); opportunities to recover energy from resulting biomass add revenue	High energy consumption contributes to depletion of limited fossil-fuel reserves; Increased emission of GHG during energy generation process degrades environmental sustainability.	7.3, 7.4, 7.5	P12: Energy for WW treatment
			8.4	P13: Energy for resource recovery
			9.2, 9.4	P14: N reduction per unit energy
			11.3, 11.6, 11.9	P15: P reduction per unit energy
			12.2, 12.9, 12.11	P16: BOD reduction per unit energy
			13.2	P17: Gross energy recovery
			17.7	
Emissions	Technologies with low harmful emissions promote better air quality, livable cities; prevent the greenhouse effect, and subsequent climate-change impacts.	Technologies with higher emission degrade air quality; contribute to greenhouse effects and climate-change scenarios.	3.3, 3.9	P18: GHG-CO_2 emissions (direct)*
			9.1, 9.4	P19: GHG –CO_2 emission (indirect)**
			11.3, 11.6, 11.9	P20: GHG-N_2O emissions
			12.4	P21: GHG-CH_4 emissions
			13.2	P22: Odor-NH_3 emissions
			17.7	
Resources recovery	Ability to recover energy and nutrients embedded in wastewater as biogas, fertilizers add revenue; conserve natural resources; mitigate environmental impacts of energy and fertilizer production	If energy and nutrients embedded in wastewater are not recovered, they are dissipated into atmosphere, surface water bodies, and land causing a series of environmental impacts.	2.3, 2.4	P23: N partitioning into gas phase
			3.3, 3.9	P24: N partitioning into sludge/biomass
			9.1, 9.2, 9.4	P25: P partitioning

Table 1 (*continued*)

Attributes of wastewater infrastructure	Opportunities	Challenges	Linkages to SDG targets	Process parameters considered
				into sludge/ biomass
			11.3, 11.6, 11.9 12.2, 12.4, 12.5 12.9	P26: Potential N recovery
			17.7	P27: Potential P recovery
Footprint	Lower space requirement of sewage treatment technologies best suited for dense urban areas with limited space; conserves natural ecosystems (e.g.: Forests)	Larger land requirement will be challenging for urban areas; can promote deforestation and loss of biodiversity; loss of visual appeal	8.4	P28: Time for wastewater treatment
			9.2, 9.4 11.9 17.7	P29: Area
Reliability/ acceptability	Technologies with longer history imply greater reliability and acceptance.	Reluctance of industries to adopt innovative and novel technologies. Limited opportunities to introduce sustainable technologies	8.2; 9.1, 9.2, 9.3, 9.4; 9.5, 9.6, 9.7; 17.6, 17.7	P30: Years of operation

*CO_2 emission due to biogenic oxidation is excluded.
**CO_2 emission during electricity generation.

evaluations. The first evaluation was done giving priority to each of the three pillars of sustainability by categorizing the 30 process parameters as environmental (P_1–P_6, P_{12}, P_{13}, P_{17}–P_{27}, P_{29}), economic (P_{12}–P_{17}, P_{26}–P_{29}), and social (P_1–P_{11}, P_{22}, P_{29}, P_{30}) parameters; however, some parameters fell into more than one category. Then, overall sustainability ranking was made considering environmental, economic, and social factors simultaneously by including the 30 parameters together.

In the second evaluation, the following 12 different scenarios (S1 to S12) were considered depending on the significance and insignificance towards several attributes of wastewater infrastructures to study the change of preference of treatment

Table 2
Sustainability assessment matrix.

	Parameter	Units	Direction	A-WWT + AD	HRAP + AD	CAS + AD	MBR + AD
P_1	Effluent BOD	mg/L	Min	14.13[a]	56[b]	25.7[c]	<5[d]
P_2	Effluent NH_4–N	mg/L	Min	5.20[a]	7.9[b]	~1.0[c]	5.6[d]
P_3	Effluent PO_4	mg/L	Min	1.00[a]	1.45[b]	~6.9[c]	~1.0[e]
P_4	Effluent COD	mg/L	Min	17.82[f]	73.87[g]	22.87[f]	12.5[e]
P_5	Effluent TN	mg/L	Min	14.37[f]	9.38[h]	31.83[f]	8.5[e]
P_6	Effluent TP	mg/L	Min	0.79[f]	3.69[h]	7.3[f]	~1.0[e]
P_7	LRV of *E. coli*	LRV	Max	5.44[i]	2.55[b]	3.04[i]	6.11[j]
P_8	LRV of Fecal coliform	LRV	Max	7.15[i]	2.04[k]	2.89[i]	6.73[j]
P_9	LRV of Somatic coliphages	LRV	Max	3.13[l]	~1.00[m]	2.51[l]	3.24[j]
P_{10}	LRV of F-specific coliphages	LRV	Max	1.23[l]	1.59[n]	4.19[l]	5.13[j]
P_{11}	LRV of ARBs	LRV	Max	3.5[o]	2.89[p]	3.15[o]	6.05[q]
P_{12}	Energy for WW treatment	kWh/m^3 of WW	Min	0.49[r]	0.82[r]	1.87[r]	2.50[s]
P_{13}	Energy for resources recovery	kWh/m^3 of WW	Min	4.170[r]	0.108[r]	0.012[r]	0.032[r]
P_{14}	N reduction per unit energy	g N/kWh	Max	61.74[r]	19.23[r]	20.60[r]	8.07[r]
P_{15}	P reduction per unit energy	g P/kWh	Max	13.76[r]	0.57[r]	0.48[r]	1.88[r]
P_{16}	BOD reduction per unit energy	g BOD/kWh	Max	129.37[r]	72.62[r]	33.56[r]	103.12[r]
P_{17}	Gross energy recovery	kWh/m^3 of WW	Max	0.46[r]	0.32[r]	0.10[r]	0.30[r]
P_{18}	GHG- CO_2 emissions (direct)[a]	kg CO_2/m^3 of WW	Min	−1.67[r]	−0.16[r]	0.011[r]	0.038[r]
P_{19}	GHG –CO_2 emission (indirect)[b]	kg CO_2/m^3 of WW	Min	2.05[r]	0.41[r]	0.82[r]	1.11[r]
P_{20}	GHG- N_2O emissions	kg CO_2 eq/m^3 of WW	Min	~0	~0	0.018[r]	0.04[r]
P_{21}	GHG- CH_4 emissions	kg CO_2 eq/m^3 of WW	Min	0.0146[r]	0.0105[r]	0.0034[r]	0.0101[r]
P_{22}	Odor- NH_3 emissions	mg NH_3/m^3	Min	~0[c]	0.0006[r]	~0[c]	~0[c]
P_{23}	N partitioning into gas phase	% relative to PE	Min	0.00[t]	2.30[c]	57.38[t]	42.5[e,r]
P_{24}	N partitioning into sludge/biomass	% relative to PE	Max	85.44[t]	65.10[c]	22.93[t]	28.5[e,r]
P_{25}	P partitioning into sludge/biomass	% relative to PE	Max	91.28[t]	24.4[c]	88.22[t]	83.0[e,r]
P_{26}	Potential N recovery	kg N/m^3	Max	0.0075[r]	0.0042[r]	0.0016[r]	0.0053[r]
P_{27}	Potential P recovery	kg P/m^3	Max	0.0051[r]	0.0028[r]	0.0011[r]	0.0036[r]
P_{28}	Time for wastewater treatment	days	Min	4[f]	8.88[b]	0.55[c]	0.38[u]
P_{29}	Area	$m^2/(m^3/d)$	Min	20[r]	25[r]	1.03[u]	0.80[u]
P_{30}	Years of operation	years	Max	6[r]	63[n]	106[v]	55[w]

a-(Tchinda et al., 2019); ***b***-(Craggs et al., 2012); ***c***-(Munasinghe-Arachchige et al., 2020); ***d***-(Melin et al., 2006); ***e***-(Bertanza et al., 2017); ***f***-field data; ***g***-(Zhou et al., 2013); ***h***-(Arashiro et al., 2018); ***i***-(Delanka-Pedige et al., 2019); ***j***-(Francy et al., 2012); ***k***-(García et al., 2008); ***l***-(Delanka-Pedige et al., 2020a); ***m***-(Davies-Colley et al., 2005); ***n***-(Young et al., 2016); ***o***-(Cheng et al., 2020); ***p***-(Mezzari et al., 2017); ***q***-(Le et al., 2018); ***r***-current study (Appendix); ***s***-(Gil et al., 2010); ***t***-(Abeysiriwardana-Arachchige et al., 2020); ***u***-(Xiao et al., 2019); ***v***-(Alleman and Prakasam, 1983); ***w***-(Fane et al., 2011).

[a] CO_2 emission due to biogenic oxidation is excluded.
[b] CO_2 emission during electricity generation.
[c] due to low pH (<9.3) ammonia volatilization in A-WWT, CAS and MBR is assumed negligible.

technologies with the decision maker's priorities: S1- high priority for pathogen removal when effluent is intended for reuse; S2- low priority for pathogen removal when effluent is disposed into restricted areas; S3- high priority for energy consumption when cost and fossil depletion are critical concerns; S4-low priority for energy consumption when energy diversification through renewable sources is enabled; S5- high priority for emission reduction where climate change impact mitigation and air quality are critical concerns; S6- low priority for gaseous emission when air is captured and treated separately; S7- high priority for resources recovery when treatment costs have to be compensated; S8- low priority for resource recovery due to extended cost for resources recovery; S9- high priority for footprint where land is limited; S10- low priority for footprint where land is freely available; S11- high priority for past records when public perceptions matters; and S12- low priority for past records when any innovative technology is accepted based on merits of the technology. High priority towards an attribute was evaluated considering the process parameters related to that particular attribute and effluent quality simultaneously. While low priorities are evaluated considering all the process parameters except the ones that related to the attribute with low priority. Categorization of process parameters into separate sustainability aspects and scenarios is detailed in Table A2 in Appendix A.

3. Results and discussion

3.1. Sustainability assessment of wastewater infrastructure

Despite the vast differences among the process parameters in the units of measurement and values, Visual PROMETHEE software normalizes them to yield a non-dimensional preference score ranging from −1 to +1 (Munasinghe-Arachchige et al., 2020). Preference scores determined for each category of sustainability (environmental, economic, and social) as well as for overall sustainability and the outcomes are discussed in the following sections.

3.1.1. Environmental sustainability

Process parameters that characterize effluent quality (P_1, P_2, P_3, P_4, P_5, P_6), gaseous emissions (P_{18}, P_{19}, P_{20}, P_{21}, P_{22}), wasteful dissipation of nutrients (P_{23}, P_{24}, P_{25}, P_{26}, P_{27}) and resource consumption (P_{12}, P_{13}, P_{17}, P_{29}) were categorized as environmentally relevant parameters. Based on the preference scores derived from these parameters, the four technologies ranked best to worst in the order of A-WWT (0.4), MBR (0.08), HRAP (−0.22), and CAS (−0.27).

The highest preference for the mixotrophic A-WWT system in the context of environmental sustainability was due mainly to low phosphorus concentration in the effluent; low energy consumption of 0.49 kWh/m^3; highest gross energy recovery of 0.46 kWh/m^3; and lowest wasteful dissipation of nutrients embedded in wastewater. Additionally, CO_2 abatement during photosynthesis of algal biomass and negligible volatile emission of ammonia resulted in a net positive preference score for the A-WWT system. MBR process also attained a net positive preference score due to better effluent quality and lowest footprint. Even though HRAP outranked CAS system, its overall preference score was negative. Although HRAPs are environmentally beneficial because of low energy consumption of 0.82 kWh/m^3; higher energy recovery of 0.32 kWh/m^3; higher recovery of N and P; and CO_2 abatement, they suffer from higher land requirement, odor emissions (NH_3) and poor effluent quality. CAS system ranked as the least preferred alternative due to relatively poor removals of PO_4, TN, TP, energy consumption of 1.87 kWh/m^3, low energy recovery of 0.10 kWh/m^3, loss of N and P, and significant emission of GHGs.

3.1.2. Economic sustainability

Although wastewater treatment by itself is a cost-intensive utility service, opportunities exist to reduce costs and generate revenues. In the economic evaluation, the following parameters were categorized to be economically relevant: energy consumption, energy efficiency of carbon and nutrients removal (P_{12}, P_{13}, P_{14}, P_{15}, P_{16}); opportunities for energy and nutrient recovery (P_{17}, P_{26}, P_{27}); and footprint (P_{28}, P_{29}). Potential for secondary benefits via reuse of high-quality effluents, reduction of disinfectant due to simultaneous pathogen reduction; saving of costs of climate change impact mitigation were not included here. In the context of economic sustainability, A-WWT and MBR processes attained positive preference scores (0.53 and 0.13, respectively), A-WWT system ranking better than the MBR system. Equal preference scores (−0.33) attained by HRAP and CAS system suggest that it might be beneficial to consider HRAP over the CAS system for sustainable wastewater treatment as the CAS system ranked below HRAP in environmental sustainability.

In the case of energy consumption for wastewater treatment, the two algal-based systems fared best due to photosynthetic aeration. Even though energy consumption of typical MBRs has been reported as 0.6–0.8 kWh/m^3, enhanced nitrogen and phosphorous removal included in the current case study necessitated higher energy demand (~2.50 kWh/m^3) to accommodate aerators and pumps (permeate, recirculation, etc.) leading to increased operation and maintenance cost and higher air emissions (Fenu et al., 2010; Gil et al., 2010; Krzeminski et al, 2012, 2017). However, recent studies have demonstrated potential modifications and optimized operations to reduce the energy consumption of MBR systems to levels low as 0.37 kWh/m^3 (Itokawa et al., 2014; Krzeminski et al., 2017; Tao et al., 2010). Adopting these modifications/optimization techniques can therefore improve the preference for MBR system in cases where energy, cost and emissions are of significant concerns. Lower biomass density and higher water content in the settled slurry in the algal-based systems necessitated higher heating energy in the anaerobic digestion step whereas, the two activated sludge-based systems fared better with higher biomass density. Energy efficiencies quantified as BOD, N, and P removed per unit energy input were highest in the A-WWT system. CAS process suffered most due to its low energy efficiency for BOD and P removal. In spite of the high energy demand in the MBR process, its energy efficiency was higher except for N, owing to high mixed liquor suspended solids (MLSS) concentration and better separation of solid via membrane barriers.

Energy recovery in the form of methane by anaerobic digestion was higher in the A-WWT system and HRAP because biomass production per unit wastewater volume was higher. Since biomass conversion ratio in AD is considered the same for all the alternatives, A-WWT and HRAP with higher biomass production resulted in higher sludge residues which could subsequently be used as agricultural fertilizer. However, MBR and CAS systems were better than the two algal systems due to the lower footprint. Even though HRAP requires significantly higher land and longer detention time, its low energy consumption and higher resource recovery make it a potential alternative for peri-urban cities where land availability may not be a major constraint.

3.1.3. Social sustainability

The following parameters were categorized as those relevant to social sustainability: downstream eutrophication potential and contact of poor-quality water (P_1, P_2, P_3, P_4, P_5, P_6); spread of harmful diseases (P_7, P_8, P_9, P_{10}, P_{11}); odor emission (P_{22}); space (P_{29}); and reliability (P_{30}). Preference scores for the treatment options were substantially different with a ranking order of MBR (0.64), A-WWT (0.17), CAS (−0.14), and HRAP (−0.67).

Better effluent quality and higher pathogen removal by membrane separation in the MBR system translated to better public acceptance as a safer and reliable alternative. Higher removal of pathogens can reduce the demand for disinfectants, and the potential for formation of disinfection by-products (DBPs) which are of serious health concerns (Delanka-Pedige et al., 2020c). In addition, low space requirement compared to the other three options makes the MBR system more attractive for communities limited by land availability. In spite of inadequate track record and space requirements, the A-WWT system ranked second in achieving social sustainability on account of high-quality effluent with negligible pathogenic bacteria. Even though CAS process suffered from moderate pathogen removal performance, its low space requirement relative to algal-based systems, lower odor emission, and over a hundred years of reliable operation contributed to a higher ranking than HRAPs. Additionally, HRAPs suffered most due to significantly higher land requirements and odor emission due to NH_3 volatilization.

3.1.4. Overall sustainability

The A-WWT system outranked the other three alternatives with an overall preference score of 0.36. Despite the moderate preference gained in social sustainability, higher preference gained in environmental and economic sustainability enabled A-WWT system to be ranked highest in terms of overall sustainability. MBR process outcompeted both CAS and HRAP systems, attaining a positive preference score of 0.21. Benefits of MBR system such as higher effluent quality in terms of chemical and microbial parameters, smaller footprint have offset its significant drawback which is the high energy consumption, in the overall sustainability assessment. Better preference for CAS system in the social sustainability owing to the long history of reliability, relatively low space requirement enabled the CAS system to be ranked better than HRAP in overall sustainability. Even though HRAP offers several environmental benefits, it ranked the last due to moderate removals of carbon, nutrients, and pathogen; and significant use of land. Rankings of the four technologies by category are compared with the overall ranking in Fig. 2. It has to be recognized that these rankings should not be taken as universally conclusive as the needs and priorities of the decision-maker can alter the preference. As such, further evaluations were done under various scenarios to ascertain if definitive conclusions could be made.

3.2. Scenario-based assessment of wastewater infrastructure

The four wastewater treatment alternatives were evaluated under 12 different scenarios considering high/low priorities of decision-makers towards six different wastewater attributes (pathogen removal, energy consumption, gaseous emission, resources recovery, footprint, and past records) while delivering high-quality effluents. Fig. 3 depicts the variation of overall preference score of the selected treatment technologies for the different priorities.

As depicted in Fig. 3, A-WWT and MBR systems consistently achieved positive preference scores for all the scenarios while HRAP and CAS systems ranked lower. The A-WWT system was the most preferred option for most of the scenarios in spite of its relatively high footprint and short history. Therefore, the A-WWT system could be the optimal option for communities and nations with favorable physical conditions (land, year-round sunlight) for algal growth. MBR system ranked higher than A-WWT system when high priority is given to pathogen removal, footprint, and past records and when low priority is given to energy consumption and resources recovery. For instance, MBR systems have been widely used for reclaiming municipal effluents where safety of the downstream application is a higher priority than the cost of energy (Qin et al., 2007). In this evaluation, HRAP outranked CAS system only when energy consumption/efficiency and resources recoveries are of high priority. However, insights gained from this scenario-based assessment are beneficial in determining which areas to be improved in order to make HRAP a potential alternative. This evaluation further demonstrates that for a given set of alternatives and process parameters, there can be infinite number of preference flows depending on decision-makers' priorities.

3.3. Weight stability of the ranking

Evaluations in this study were conducted assigning an equal weight of 1.0 to parameters of concern to avert any emotional bias on a particular technology; weighting factors depend on decision-makers' priorities and the rankings could be sensitive to the weighting factors. Weighting of criteria plays a critical role in MCDM evaluation and suitable weights are determined mostly based on probability distribution methods or previous studies (Maghrabie et al., 2019). Determining accurate weights becomes difficult when sufficient data are not available (Maghrabie et al., 2019). Visual PROMETHEE software offers built-in functions to determine weight stability intervals for each parameter selected for evaluation. Exceeding the stable weight range alters the preference ranking where higher the range greater the stability of ranking and *vice versa*. Criteria with narrow weight stability intervals could be highly sensitive and have a greater potential to alter the ranking if not accurately assigned. Among the 30 process parameters considered in this study, weight stability intervals in the case of P_5, P_{10}, P_{13}, P_{17}, P_{20}, P_{21}, P_{23}, P_{24}, P_{28}, and P_{29} were <15% implying that these parameters are the most sensitive ones and have to be weighted with care. Weight stabilities in the case of P_8 and P_{22} were 100%, implying that the ranking is insensitive to weights of these two parameters. Moderate weight stability intervals were found for the rest of the process parameters. Weight stability intervals for the 30 process parameters are tabulated in Table A3 in Appendix A.

3.4. Sensitivity analysis

As part of this study, we determined the sensitivity of the preference scores to ±10% variations (one value at a time) in the evaluations of the 30 parameters ($P_1 - P_{30}$) for each of the four alternatives, under the 16 scenarios (Results of this exercise are included in the SI section). From environmental and overall sustainability perspectives, P_{25} was found to be the most sensitive parameter with a percentage sensitivity of 80.1 and 21.1, respectively. From the economic sustainability perspective, gross energy recovery (P_{17}) was found as the most sensitive parameter (50%); and, from the social sustainability perspective, reduction of ARBs (P_{11}) was found as the most sensitive one (33.3%). In the case of scenario-based evaluation, P_{25} was the most sensitive parameters for S2, S4, S6, S7, S10, and S12 with percentage sensitivity of 66.6, 20.0, 16.7, 44.4, 30.7, and 20, respectively. Following *P25*, parameter P_2 was sensitive towards S1 (20.0%), S3 (28.6%), S5 (33.3%), S9 (40.0%), and S11 (50.0%). The preference scores were not found to be sensitive to 21 remaining parameters (P_1, P_3, P_4, P_6, P_7, P_{10}, P_{12}, P_{13}, P_{15}, P_{16}, P_{18}–P_{20}, P_{22}–P_{24}, and P_{26}–P_{30}) under any scenario. These findings of the sensitivity analysis could be beneficial, for example, in determining whether a proposed modification to an existing technology (e.g.: integrating resources recovery, improved disinfection, etc.) or proposed alternative is worthy of consideration from a particular sustainability perspective or scenario. Further details of the sensitivity analysis are included in Appendix B.

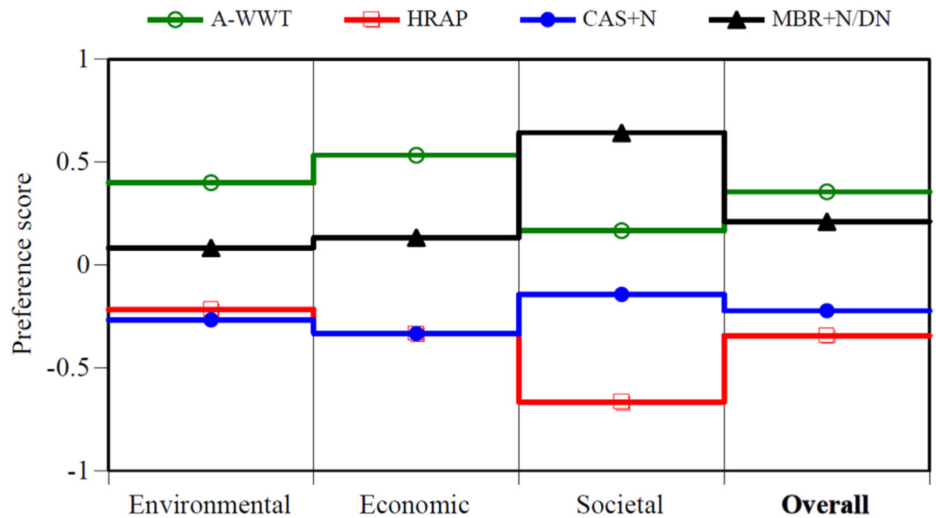

Fig. 2. Sustainability assessment of the four wastewater treatment alternatives.

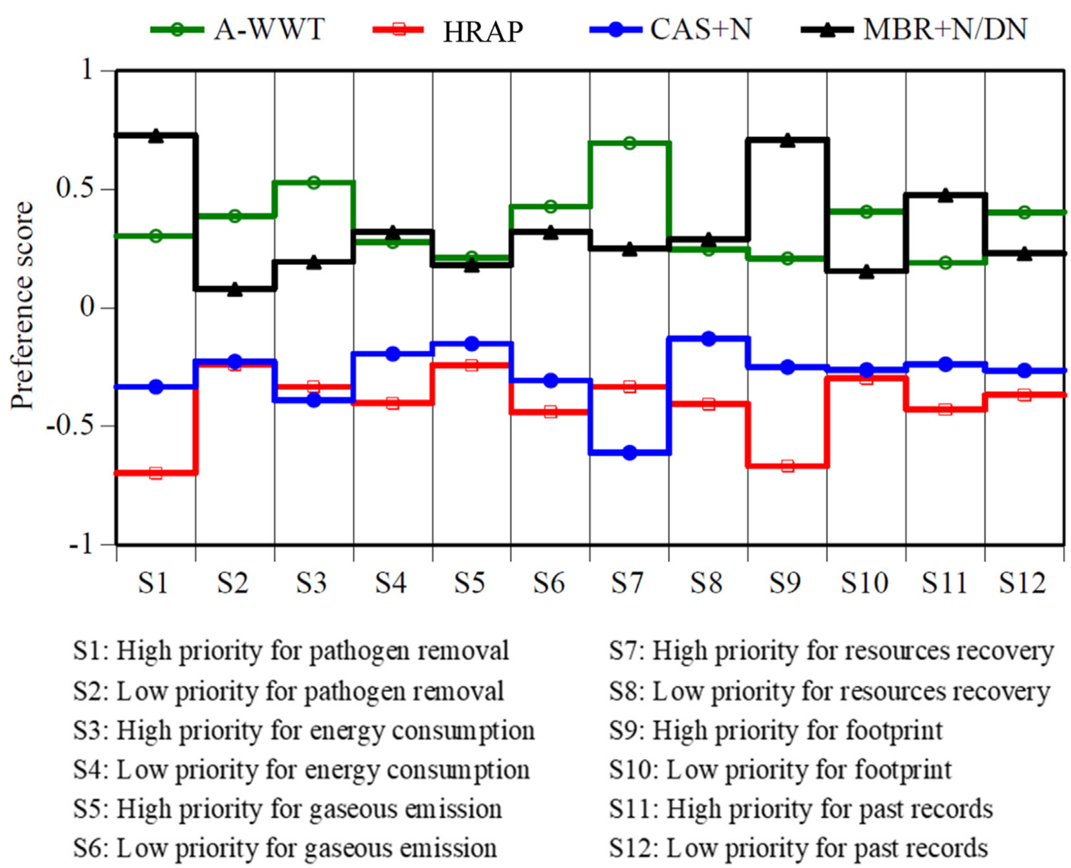

Fig. 3. Variation of the preference score based on different priorities of the decision-maker.

3.5. Comparison with literature

3.5.1. Summary of methods/indicators used to select optimal treatment option

Previous studies have reported on a variety of approaches for comparing alternatives for sustainable urban infrastructures: some focusing on the environmental dimension [Environmental Impact Assessment-EIA, Life Cycle Analysis-LCA, Ecological Footprints-EF, etc. (Abyar et al., 2020)]; some on economic (Cost-Effectiveness Analysis-CEA, Cost-Benefit Analysis-CBA, Multi-criteria decisions aid-MCDA, etc.); and some on social (Social Impact Assessment-SIA, Socio-Economic Impact Assessment-SEIA, etc.) (Šijanec Zavrl and Tanac Zeren, 2010). A few studies have adopted certain measures combining two or more of the above approaches and ranking the alternatives using MCDA or the analytic hierarchy process (AHP).

Previous studies have proposed specific sustainability-related measures to evaluate alternate wastewater technologies, most of them considering the economic and technical aspects with a few considering the social aspects as well. Muga and Mihelcic (2008) were among the first to propose sustainability-related measures to compare wastewater technologies where, three economic, six environmental, and six societal indicators were used to compare mechanical, lagoon, and land treatment systems for wastewater treatment. Molinos-Senante et al. (2014) have used 17 measures (2 economic, 11 environmental, and 5 societal measures) to compare 7 alternate WWT technologies (constructed wetlands; extended aeration; membrane bioreactor; rotating biological contactor; trickling filter; and sequencing batch reactor). In a recent study, Arroyo and Molinos-Senante (2018) have modified the previous study considering 10 environmental and 5 societal measures and excluding economic measures; it was rationalized that since cost is a constraint and not a value, preliminary process evaluations should be based only on environmental and societal measures.

3.5.2. Gaps in the previous evaluations

In the early era of wastewater treatment, technical aspects such as carbon and nutrient removal, reliability, durability, adaptability, maintenance requirement, flexibility to varying waste loads, etc. have been given the highest priority in selecting appropriate technology (Balkema et al., 2002). With the advancement of new technologies and improvements to existing technologies, economic impacts for instance energy consumption, footprint, capital cost, operation and maintenance cost, and sustainability are included in addition to technical performances (US EPA, 1997). Although the indicators/measures used in previous studies are related to the economic-social-environmental pillars of sustainability, their linkages to the current SDGs have not been explicitly identified. For instance, Balkema et al. (2002) have reviewed potential indicators and tools to determine sustainability of wastewater treatment systems. Another study proposed a path to conduct LCA to better integrate multiple sustainability concerns on urban water and wastewater systems and did not address demands on SDGs (Byrne et al., 2017). Even though Chen et al. (2020) demonstrated a footprint assessment for wastewater treatment systems to determine their sustainability and concluded water-carbon-energy nexus as a hotspot for future research, they did not acknowledge the importance of integrating UN SDG aspects. Also, a study by Vidal et al. (2019) had presented MCDM assessment of on-site sanitation systems based-on environmental, economic, socio-cultural, technical and health criteria, but without linking them to SDGs.

Even though public safety is of prime importance, evaluating social aspects was found to be difficult due to the lack of measurable indicators. Only a limited number of literature reports had accounted pathogen control in selecting appropriate wastewater treatment technologies. A thorough review of LCAs on urban water infrastructures had recognized the importance of accounting microbial indicators for public health-related concerns (Byrne et al., 2017). For instance, Vidal et al. (2019) used a qualitative scale ranging from very low to very high to evaluate health risk of nine different on-site sanitation technologies and the health concerns were given lower priority compared to resources recovery, energy and climate change concerns in evaluating overall sustainability. Similarly, another study reviewed onsite sanitation technologies for their suitability in achieving multiple SDGs. However, their assessment was oriented more on nutrient recovery and less on health risk (Orner and Mihelcic, 2018).

Most of the indicators applied in previous studies are general, conceptual, and often qualitative. Hence, it's difficult to measure the degree of contribution of multiple alternatives towards attaining UN SDG targets. In comparison, indicators/process parameters proposed in the current studies are specific, measurable, attainable, real, and closely linked to sustainable development targets. These indicators are relatively flexible and certain indicators can be used to assess different scenarios. For instance, effluent quality measured as BOD, COD, $NH_4{-}N$, PO_4, TN, and TP could be indicators of freshwater and marine eutrophication as well as for potential for water reuse and cost-saving on tertiary treatment; emission of CO_2, N_2O, CH_4 could be indicators for poor air quality, global warming potential, and cost-saving on climate change impact mitigation; log removal of *E. coli*, fecal coliform, coliphages, ARBs could be indicators of potential for prevention of water-borne diseases, cost-saving on disinfectants and reduction of DBP formation. However, the current evaluation did not consider capital and operation/maintenance costs, labor intensiveness, cost of sludge handling, etc. in assessing economic sustainability due to lack of consistent data for the alternatives considered here.

3.5.3. Comparison of ranking

Previous studies have evaluated different wastewater treatment technologies using LCA, techno-economic, and MCDA approaches. The current study differs from the previous efforts in several aspects; 1) comparison of two algal pathways with well-established activated sludge systems; 2) simultaneous consideration of environmental, economic, and social sustainability; 3) assessment of several priority-based scenarios; and 4) assessment of technologies in the context of UN SDGs and their targets. To the best of our knowledge, use of SDGs and their targets in evaluating activated sludge-based wastewater infrastructure systems using MCDM tools has not been reported previously.

A study by Hao et al. (2018) conducted a sustainability-based assessment comparing MBR system with CAS system considering capital cost, operational cost, footprint, energy consumption, resources recovery, and other managerial aspects. They concluded that, in spite of its superior effluent quality and smaller footprint, MBR is an unsustainable option compared to CAS due to higher energy consumption and higher operation/maintenance costs (Hao et al., 2018). A study by Karim and Mark (2017) reported that even though CAS system outperformed MBR system in terms of cost-effectiveness, for long-term operation, MBR system might fare better than CAS system due to lower footprint and treatment efficiency. Similarly, a study by Bertanza et al. (2017) reported a slightly better overall preference score for CAS system over MBR system due to costs, energy and complexity; however, MBR system was ranked better when social aspects are given importance. In contrast to previous reports, the MBR system ranked better than CAS system in all the cases in the current study because of the higher P removal via aluminum sulfate addition and higher N removal due to denitrification process. Unlike in a previous study by Bertanza et al. (2017) that accounted only removal of C, N, P, and solids for evaluating sustainability of MBR vs CAS system, the current study considered pathogen removal as one of the process parameters. Hao et al. (2018) also did not acknowledge pathogen removal performance when comparing MBR with CAS system. The superior performance of MBR system in removing pathogens contributed to its higher ranking in the current study.

Arashiro et al. (2018) conducted an LCA to compare HRAP with biogas production and CAS system without biogas production considering 11 environmental impact categories such as climate change, ozone depletion, acidification, eutrophication, metal and fossil depletion, and toxicity. However, they did not account for the significance of CO_2 abatement and pathogen removal in their evaluation. They further stated that climate conditions in different demographics might influence biomass growth and efficiency of wastewater treatment could be different (Arashiro et al., 2018). The higher consumption of materials and resources for construction and hence the increased capital cost for HRAPs were identified as challenges. Even though HRAPs rank better than CAS systems in climate change impacts, depletion of the ozone layer, and depletion of fossil fuels, they suffer due to acidification, toxicity, and particulate matter formation (Arashiro et al., 2018). Our findings are in line with those of Arashiro et al. (2018) ranking HARP better than CAS system in terms of environmental sustainability, energy efficiency, and resource recoverability. Even though HRAP was least preferred in most of the cases, there are opportunities to improve HRAP technology by minimizing NH_3 volatilization and heavy metal release through biomass and maximizing nutrient removal efficiencies. Adopting this technology would be more economical in areas where favorable climatic conditions and space are freely available (Arashiro et al., 2018). It has been demonstrated that wastewater treatment by HRAP can be energy positive if the biomass is co-digested with primary sludge to generate electricity or heat (Passos et al., 2017). Adopting more efficient and effective resource recovery pathways (e.g. hydrothermal liquefaction process followed by struvite recovery) also could improve the sustainability of HRAPs (Munasinghe-Arachchige et al., 2020).

Our previous reports have demonstrated that the emergent mixotrophic A-WWT system integrated with resources recovery could be a potential alternative to energy-consuming CAS systems (Abeysiriwardana-Arachchige et al., 2020). Also, superior performance of the A-WWT system over the classical photoautotrophic HRAPs in volumetric removal of C, N, and P (Tchinda et al., 2019), inactivation of pathogenic bacteria and viruses (Delanka-Pedige et al., 2020a), and recovery of nutrients and energy (Abeysiriwardana-Arachchige et al., 2020) has been discussed.

4. Conclusions

This study presented a multi-criteria comparison of two activated sludge-based (conventional activated sludge and membrane bioreactor) and two algal-based (High-Rate Algal Pond and mixotrophic algal wastewater treatment) systems in their ability to serve as sustainable wastewater infrastructure facilities. The significance of the current evaluation is that the comparison was done on the basis of 30 process parameters derived from the UN Sustainable Development Goals (SDGs) and their targets. These parameters enabled the multi-criteria decision-making approach to be applied in this comparison under 3 different sustainability aspects and 12 different scenarios/priorities. In most cases, the emergent mixotrophic algal system ranked as the most preferred one, followed by the membrane bioreactor. Comparison with literature reports using other methods of comparisons indicated that the findings of the current study are comparable with the reported ones. However, in contrast to previous studies, the proposed approach affords a quantitative evaluation using parameters that are directly or indirectly linked to the UN SDGs. Feasibility of incorporating local priorities and limitations in the process of decision-making enables widespread applicability of the proposed approach and thereby contributes to the progress towards meeting the SDGs of the UN 2030 Agenda for sustainable development.

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CRediT authorship contribution statement

Himali Madushani Kanchanamala Delanka-Pedige: Formal analysis, Lead author; literature review; overall concept design; data compilation and analysis; integration/discussion of results. **Srimali Preethika Munasinghe-Arachchige:** Co-author; contributed to MCDM analysis; authored sections on MCDM; review and revision of manuscript. **Isuru Sachitra Abeysiriwardana Abeysiriwardana-Arachchige:** Formal analysis, Writing – original draft, Co-author; contributed to process analysis; authored sections on process evaluation; review and revision of manuscript. **Nagamany Nirmalakhandan:** Supervision, Securing funding, overall supervision/coordinating, review and revision of manuscript, graphic preparation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126795.

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