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DOI
10.1016/j.jclepro.2022.134005

Publication date
2022

Document Version
Final published version

Published in
Journal of Cleaner Production

Journal of Cleaner Production 374 (2022) 134005

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A comparative evaluation of the sustainability of alternative aeration strategies in biological wastewater treatment to support net-zero future

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ARTICLE INFO

Handling Editor: Yee Van Fan

Keywords:
Sustainable development
Net zero
Climate change
Wastewater treatment
Life cycle analysis

ABSTRACT

In the plight for sustainable development and to support net zero ambitions for climate change mitigation, a broad range of aeration strategies have been developed with the hope of improving efficiency to minimize environmental and economic costs associated with the wastewater treatment processes. However, a balance is levied between reducing oxygen availability and hindering aerobic processes thus compromising performance. In the present work, we evaluate and compare the sustainability of a range of investigated strategies including continuous aeration (CA) at different dissolved oxygen (DO) setpoints (0.5 mg/L, 2.5 mg/L, 4.5 mg/L) and intermittent aeration (IA) at different oxic-anoxic portions (2.5 h on/0.5 h off, 2.0 h on/1.0 h off, 1.5 h on/1.0 h off). To achieve this, an eco-efficiency assessment is performed based on the results of previous life cycle impact and costing analyses for each strategy, while also incorporating a third factor to account for their respective treatment performance. The results demonstrate a clear pattern of increased sustainability for the IA strategies (0.54–0.56 Pt/m^3), compared to the CA strategies (0.76–0.77 Pt/m^3). While only negligible difference was observed within each aeration type, the trade-off between environmental and economic efficiency and treatment performance was distinct in CA strategies. At the individual pollutant level, IA strategies demonstrated decreasing sustainability for total phosphorous (TP) removal as the anoxic cycle portion increased, while CA at 0.5 mg/L was shown to be the most sustainable strategy for the removal of this pollutant (0.61 Pt/m^3). Further work is suggested to incorporate the relative N_2O emissions generated by each strategy and to investigate other strategies based on automated control.

1. Introduction

Sustainability is becoming an increasingly critical aspect of decision making in wastewater treatment selection (Kalbar et al., 2012). Global efforts to achieve the sustainable development goals (SDGs) as laid out in the United Nations 2030 Agenda for Sustainable Development in 2015 has driven increased favour for more environmentally-sensitive infrastructure (Thacker et al., 2019). In fact, the UK water sector has set the ambitious target of delivering a net zero water supply by 2030 to aid the mitigation of climate change (Water UK, 2022). Wastewater treatment provides something of a paradox in the plight for sustainability. While it plays a critical role in preserving ecosystem quality and human health, the technologies required to achieve this can often impose their own significant environmental burden (Kamble et al., 2019). Despite there being a range of eco-friendly technologies now available, their suitability is often circumstantial due to a trade-off of other favourable characteristics such as small footprint or high treatment performance (Crini and Lichtfouse, 2019). In many cases such as in urban settings, land availability for wastewater treatment is often limited and technologies that typically incur a higher environmental burden continue to be necessitated (Capodaglio and Olsson, 2019). As such, efforts to enhance the sustainability of these technologies remains warranted.

Aeration can account for between 50 and 90% of the electricity consumed by a wastewater treatment plant (Drewnowski et al., 2019). This is particularly true in biological technologies that utilize high aeration rates to reduce land requirements such as the integrated fixed-film activated sludge (IFAS) system (Rosso et al., 2011). In countries that still rely heavily on carbon-rich energy sources this can be highly detrimental to the environmental profile of the treatment technology (Polruang et al., 2018). Fossil energy use has been demonstrated to be the main driver of environmental burden in production (Huijbregts

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https://doi.org/10.1016/j.jclepro.2022.134005
Received 5 June 2022; Received in revised form 26 August 2022; Accepted 2 September 2022
Available online 7 September 2022

et al., 2010), being responsible for several detrimental impacts on the environment such as air pollution, global warming, and resource depletion (Martins et al., 2019). Aside from the heavy environmental cost of aeration, the ongoing financial costs to operate these energy-intensive plants can also limit their sustainability from an economic standpoint. In fact, previous work has shown the operational phase of aerobic wastewater treatment systems can account for over 95% of total plant costs in some cases (Kamble et al., 2018).

In view of the potential that IFAS offers in urban wastewater management, increasing work has sought to identify more efficient oxygen strategies that may alleviate some of these costs without compromising on performance. The most direct way to achieve this is to optimize the amount of oxygen provided in the reactor and limit the excess. Sriwiriyarat et al. (2008) found that sufficient total nitrogen (TN) removal could be achieved in the IFAS at a lower DO concentration of 2 mg/L providing the carbon:nitrogen (C/N) ratio of the influent was favourable. More recently, Li et al. (2016) recommended a reduction from 8 mg/L to 4 mg/L to be sufficient in an IFAS reactor. Singh et al. (2016) found that a similar level of TN removal could be achieved in a package IFAS system when the aeration was reduced from 4.5 mg/L to 2.5 mg/L. This they attributed to the occurrence of simultaneous nitrification and denitrification (SND) which is a more efficient form of TN removal than the conventional oxic-anoxic process, due to its reduced aeration and footprint requirements.

Another approach to improved energy-efficiency is the incorporation of a rest period in the aeration cycle (Dan et al., 2021), otherwise known as intermittent aeration (IA). Several studies have shown this strategy to yield high treatment performance despite the reduced output of total aeration. While settling quality of the sludge was seen to be adversely affected due to a lack of supplementary mixing, Singh et al. (2017a) reported strong removal efficiencies in an IA-operated IFAS system in spite of this. Iannacone et al. (2020) demonstrated that good treatment performance could also be maintained in a similar technology, the moving bed biofilm reactor (MBBR) when operated under IA. Yang et al. (2020) also reported excellent nitrogen removal in an IFAS system treating highly concentrated supernatant when operated under IA.

It is clear that changes in the aeration approach can be beneficial for energy-efficiency, however it is less clear how the sustainability of different aeration strategies compare from an environmental, economic and technical perspective. The aim of the present work was to evaluate and compare the sustainability of 6 prominent aeration strategies used in IFAS systems. To achieve this, a modified version of the eco-efficiency index (EEI) was developed. The EEI assesses sustainability by relating the environmental performance of a product system to its product value (EN ISO 14045: 2012), and has been used to evaluate the sustainability of various aspects of wastewater management. Resende et al. (2019) used the eco-efficiency assessment (EEA) to compare the sustainability of different constructed wetland (CW) configurations, while Mocholi-Arce et al. (2020) used this method to compare the sustainability of 30 wastewater treatment plants (WWTPs). A limitation of this approach is that it neglects the influence of alternative scenarios on treatment performance, instead assuming sufficient treatment is achieved. However, this cannot always be assumed, as demonstrated by aeration where alternative strategies are known to have profound effects on treatment performance (Singh et al., 2016). To overcome this, a tri-factor sustainability index (TFSI) was here developed to incorporate the treatment performance of key pollutants as an additional element to the two-factor EEI used in other work that considers only economic and environmental impact factors (Canaj et al., 2021).

To the best of our knowledge, this is the first work of its kind to consider alternative aeration strategies from an eco-efficiency perspective despite aeration incurring the greatest environmental and economic costs in biological wastewater treatment (Kamble et al., 2019). It is hoped the findings of this work will better inform decision makers involved in urban development and pollution mitigation, and provide a more holistic tool for assessing sustainability in water treatment systems.

2. Method

2.1. Study system

The system being investigated in the present work is a package IFAS system that has previously been described in detail (Singh and Kazmi, 2016). In short, wastewater influent is provided straight to the main reactor at a flow rate (Q) of 69.6 m^3/d. As shown in Fig. 1, the IFAS system consists of a 20 m^3 aerobic reactor containing 64c Cleartec Biotextil® media sheets (2.7 m × 0.96 m), four Aerostrip® T1.5-EU-18 air diffusers and a stainless steel (SS) media frame. Aeration is supplied by a commercial blower at varying rates as described in Table 1. Following the main reactor is a 4.2 m^3 circular settlement tank with conical base. From here effluent is released into the environment, while waste activated sludge (WAS) is drawn at a rate of 1.1 m^3/d. Recycle activated sludge (RAS) is also returned to the start of the aerobic reactor from the base of the settlement tank at a rate of 87 m^3/d.

2.2. Goal and scope descriptions

The goal of the present study is to investigate the sustainability of 6 alternative aeration strategies. For each the TFSI is calculated based on environmental scores from a previous life cycle impact assessment (LCIA) of the investigated strategies (Singh et al., 2020), the economic costs incurred from a previous life cycle costing analysis (LCCA) of the same strategies (Pryce et al., 2022), and the average treatment performance of these strategies as previously reported (Singh et al., 2017b). LCIAs and LCCAs have been considered as the most appropriate tool for evaluating environmental and economic costs during optioneering of wastewater solutions (Kamble et al., 2019). Scores used in the TFSI calculation are based on 1 m^3 treated wastewater which is the functional unit used in each life cycle analysis (LCA). For each LCA, the system was investigated in an Indian context to be consistent with the underlying work that has contributed data to the present study. Further details regarding the formats of these analyses can be found in the respective publications (Singh et al. 2017b, 2020; Pryce et al., 2022).

2.3. Tri-factor sustainability index (TFSI)

In the present work, the TFSI was calculated to provide a holistic perspective of the sustainability of each aeration strategy. While the last two decades have seen the development of several advanced decision support tools (DSTs) used for optioneering sustainable wastewater solutions using different criteria, their application in evaluating individual aeration strategies is limited due to the choice of indicators employed. For example, while Chamberlain et al. (2013) developed a capable decision support system to aid design and evaluation of sustainable water solutions based on economic, environmental and social criteria, its lack of consideration for performance makes it unsuitable for the present investigation. In contrast, Di Fraia et al. (2018) developed a class-based method for wastewater treatment that defines energy performance indicators (EPIs) based on the relationship between energy consumption and the removal efficiencies of individual parameters. While it is an effective means of relating performance to electrical efficiency, its application as an index of sustainability is limited, as it fails to account for the environmental aspect.

In order to ensure equal weighting of each factor, the total score was comprised of an equal contribution of each. In the case of the TFSI, each of the three factors would contribute a third of the total score, while in contrast each of the two factors in the EEI would contribute half of the total score. Alternatively, factor weighting could be manipulated by adjusting the relevant contributions.

The calculations were performed as according to Equation (1):

$$TFSI = \left[\frac{EnS_n}{EnS_{max}}\right]\frac{1}{WI_n} + \left[\frac{EcS_n}{EcS_{max}}\right]\frac{1}{WI_n} + \left[\frac{PS_n}{PS_{max}}\right]\frac{1}{WI_n} \tag{1}$$

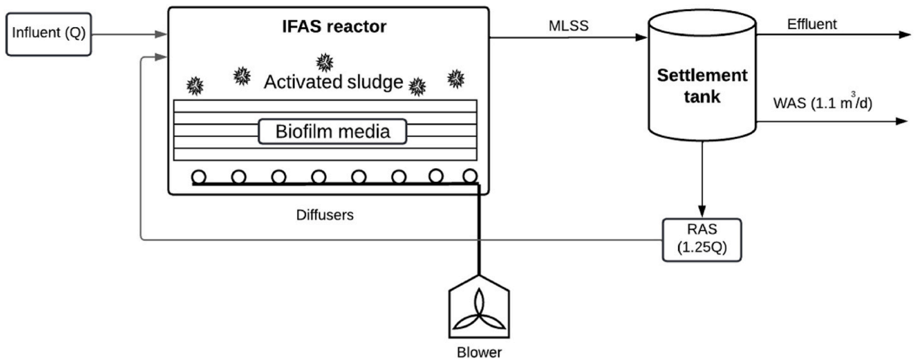

Fig. 1. Configuration of the package IFAS system.

Table 1
Aeration strategy definitions.

Strategy Code	Description
CAI	Continuous aeration delivering a dissolved oxygen level of 0.5 mg/L
CAII	Continuous aeration delivering a dissolved oxygen level of 2.5 mg/L
CAIII	Continuous aeration delivering a dissolved oxygen level of 4.5 mg/L
IAI	Intermittent aeration delivering dissolved oxygen of 2–3 mg/L when active for 150 min followed by 30 min of no aeration.
IAII	Intermittent aeration delivering dissolved oxygen of 2–3 mg/L when active for 120 min followed by 60 min of no aeration.
IAIII	Intermittent aeration delivering dissolved oxygen of 2–3 mg/L when active for 90 min followed by 30 min of no aeration.

where EnS_n = The environmental score of strategy n, EnS_{MAX} is the highest environmental score of all the strategies, and WI_n is the relative weighting given to each indicator n given as a decimal fraction of 1 (i.e. 0.5 for a 2 x weighting relative to the other 0.25 indicators or 0.333 for equal weighting). EcS_n is the economic score of strategy n and EcS_{MAX} is the highest environmental score for this indicator. Finally, PS_n is the overall performance score of strategy n and PS_{MAX} is the highest performance score achieved for this indicator.

In order to incorporate treatment performance into the TFSI, it was necessary to first derive a single index score that would reflect the capacity of the system to treat a range of pollutants that represent wastewater effluent quality. Pollutants considerd in the present work include chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), TN and total phosphorus (TP). To achieve this the water pollution index (*WPI*) was used as described by Hossain and Patra (2020). This was calculated as accoridng to Equation (2) (Hossain and Patra, 2020):

$$\text{Water Pollution Index, } WPI = \frac{1}{n}\sum_{i=1}^{n} 1 + \left(\frac{C_i - S_i}{S_i}\right) \tag{2}$$

where n is the number of parameters being integrated, C_i is the effluent concentration of the i_{th} parameter and S_i is the effluent limit for that parameter as designated by the Central Pollution Control Board (CPCB) India in this case. Table 2 displays the effluent limits following update by the Ministry of Environment, Forest and Climate Change (MoEFCC) in 2015 for enhanced stringency as part of the National River Conservation Plan (NCRP) as well as the reported effluent concentrations under each strategy (Singh et al., 2017b).

Environmental impacts of each aeration strategy were considered in terms of the endpoint categories following the previous LCIA performed by Singh et al. (2020). This was of value because the latter approach provided a common unit for each endpoint category that could be combined to calculate an overall TFSI score for each strategy as well as per category (human health, ecosystem quality, climate change and resources). This allowed for investigation into the sustainability of each aeration strategy under different environmental priorities. Endpoint impact scores were derived using the IMPACT 2002+ method (Jolliet et al., 2003), that provides scores in a common unit at the normalized damage level named "points". Each point represents the average impact in each of the four endpoint categories caused by a person during one year in Europe (Jolliet et al., 2003). Endpoint scores as reported by Singh et al. (2020) are shown in Table 3.

In consideration for the economic indicator, costs were taken from the LCCA performed by the author (Pryce et al., 2022). For the sake of the TFSI, only the energy costs associated with aeration were considered in order to correspond with the relevant impacts. In order to account for future change in monetory value throughout the 15 year service life based on current predictions of inflation and interest rates, energy costs were calculated in terms of net present value (NPV). The NPV was calculated by way of the following equation (Younis et al., 2018):

$$\text{Life cycle cost, } LCC\ (\$/m^3) = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{3}$$

where T is the service life expressed in years, C_t is the annual energy costs in this case, t is each year, and r represents the real discount rate that is a function of expected inflation and interest rates. Results of this analysis are displayed in Table 5.

Table 2
CPCB effluent limits (mg/L) for the considered parameters (Ministry of Environment, Forest and Climate Change, 2015) and effluent concentrations for each strategy as reported by Singh et al. (2017b).

Parameter	Limit	CA I	CA II	CA III	IA I	IA II	IA III
COD	50	85	61	25	34	30	42
BOD	10	46	31	9	18	14	19
TSS	20	59	38	15	15	16	15
TN	10	43	14	14	11	12	11
TP	1	0.77	0.93	0.59	0.88	1.25	1.43

Table 3
Impact scores of each strategy reported by Singh et al. (2020) for each endpoint impact category and total.

Impact category	Unit	CA I	CA II	CA III	IA I	IA II	IA III
Human health	Pt	7.11	9.49	11.12	7.00	6.59	6.45
Ecosystem quality	Pt	7.71	7.78	7.73	7.50	7.48	7.49
Climate change	Pt	3.46	4.65	5.42	3.40	3.19	3.13
Resources	Pt	2.58	3.34	3.89	2.40	2.25	2.21
Total	Pt	20.85	25.25	28.16	20.31	19.51	19.28

Table 5
Economic costs of each aeration strategy as reported by Pryce et al. (2022).

Indicator	Unit	CA I	CA II	CA III	IA I	IA II	IA III
Economic	$\$/m^3$	0.09	0.12	0.15	0.09	0.08	0.08

3. Results

3.1. Three-factor sustainability index analysis

Each of the indicator scores of the TFSI used within the sustainability analysis are provided as per Table 6, with the treatment performance scores calculated as per the WPI. A lower score is favoured for each.

The results of the TFSI sustainability analysis were seen to be influenced by the addition of the third indicator when compared to the conventional two-factor analysis. According to the EEI results in Fig. 2a, CA I was shown to offer a considerably greater sustainability (0.65 Pt/m^3) compared to CA II and CA III that scored 0.86 Pt/m^3 and 1.00 Pt/m^3 respectively. In fact, CA I displayed a similar eco-efficiency to the IA strategies that demonstrated similar scores ranging between 0.61 and 0.66 Pt/m^3. However, by incorporating the treatment performance indicator, the CA strategies were comparable in sustainability (0.76–0.77 Pt/m^3), with CA III offering the greatest treatment performance of all investigated strategies. As can be seen in Fig. 2b, by incorporating the third indicator the trade-off between performance and reduced energy consumption is made apparent. It is also clear that the sustainability of the CA strategies is thematically worse than the IA strategies, which maintained similar TFSI scores between 0.54 and 0.56 Pt/m^3. At their core, the energy and treatment performance differences between the IA strategies were less accentuated which explains their tighter grouping in the sustainability analysis.

Further consideration was given to the influence of relative weighting on TFSI scores. In sustainability analysis, the effect of assigned indicator weights on results are known to be profound (Gumus et al., 2016). Gumus et al. (2016) reported statistically significant differences between weighting strategies in their EEA of different manufacturing sectors in the United States. Mocholi-Arce et al. (2020) also highlighted the importance of weight allocation when estimating the eco-efficiency score of WWTPs. In wastewater treatment, it can be argued that performance warrants a higher weighting than the relative environmental or financial burden of candidate technologies, as a lack of adequate treatment would negate the justification of providing the technology as a plausible solution. Starkl et al. (2018) emphasized the importance of not compromising treatment performance when comparing the economics of potential technologies due to the legal obligations of fulfilment.

Results of the weighting assay showed that an increased weighting of either the impact or economy indicators to 50% (vs 25% for remaining indicators) had little effect on the outcome of the EEA. However, when treatment performance was given increased value in the TFSI, sustainability scores were seen to be largely affected as displayed in Fig. 3. IA strategies remained the most sustainable alternatives but with scores substantially reduced by as much as >0.15 Pt/m^3. IA II was seen to be the most favourable alternative with 0.34 Pt/m^3 with IA I and IA III scoring 0.35 Pt/m^3 and 0.36 Pt/m^3 respectively. The greatest contrast

Table 6
Environmental, economic and treatment performance of each aeration strategy.

Indicator	CA I	CA II	CA III	IA I	IA II	IA III	Reference
Environment	1.06	1.32	1.49	1.07	1.03	1.01	Singh et al. (2020)
Economic	0.09	0.12	0.15	0.09	0.08	0.08	Pryce et al. (2022)
Treatment performance	2.86	1.71	0.83	1.04	1.05	1.20	Calculated

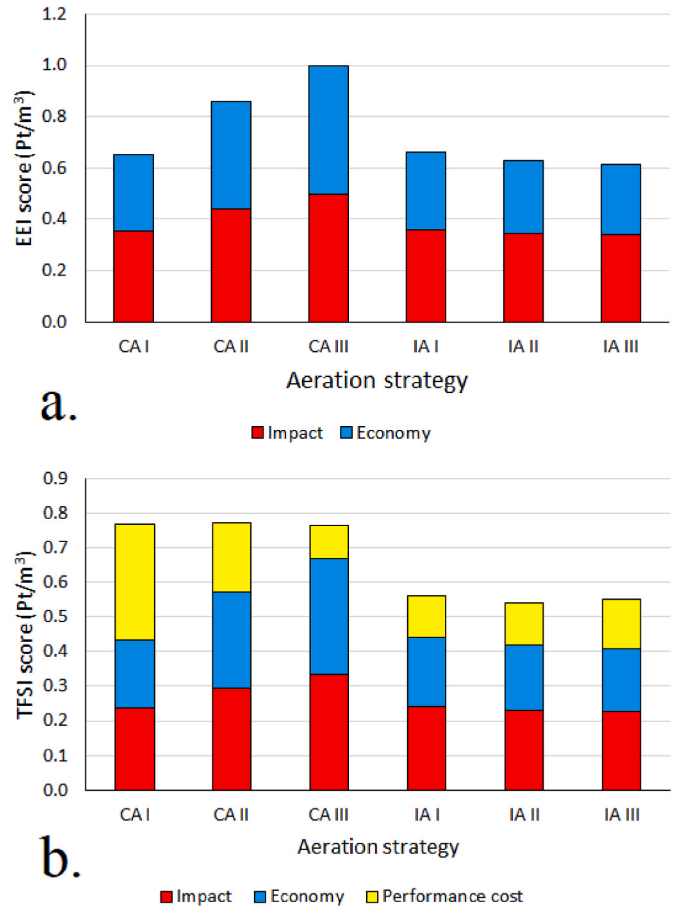

Fig. 2. Sustainability scores for each of the aeration strategies represented by a. the EEI and b. the TFSI.

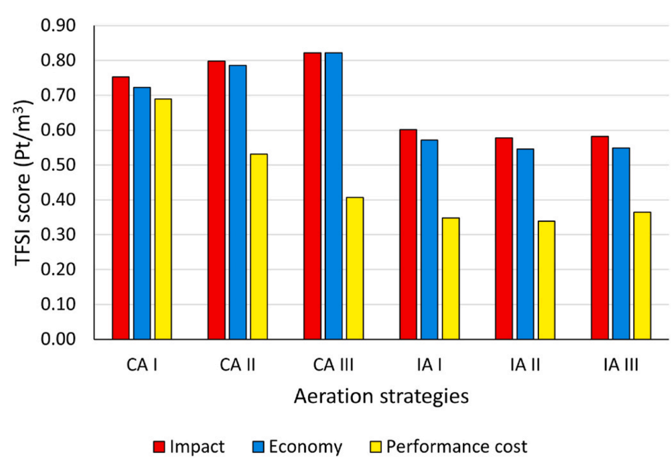

Fig. 3. Weighting influence on TFSI for each aeration strategy. Factors displayed with double weighting accounting for 50% of the TFSI score (vs 25% for remaining indicators).

was observed between the CA strategies. While CA I demonstrated little variability between assigned weighting, CA II and CA III saw substantial gains in implied sustainability with the latter receiving a score of only 0.41 Pt/m^3 compared to the 0.76 Pt/m^3 scored at equal weighting.

3.2. Environmental impact contribution

Investigation at the impact category level showed CA III to be the least sustainable option of all strategies overall. While IA strategies demonstrated very little difference between categories as shown in Fig. 4, CA strategies had varying levels of asymmetry depending on the category being included in the TFSI. For human health, the difference between CA strategies was most pronounced with CA III scoring 11.12 Pt/m^3 compared to 9.49 Pt/m^3 and 7.1 Pt/m^3 for CA II and CA I, respectively. This pattern remained valid for climate change and resources but with reduced asymmetry of <2 Pt/m^3 between CA III and CA I in the former category and <1.5 Pt/m^3 in the latter. Contrary to this pattern, sustainability provoked little influence from the choice of aeration strategy in terms of ecosystem quality with all TFSI scores ranging between 7.48 and 7.78 Pt/m^3. This relative symmetry relates to the reduced impact incurred by CA III in the EU midpoint category as shown in previous work (Singh et al., 2017b), with this being a pathway category for the ecosystem quality endpoint category in the IMPACT 2002+ method (Jolliet et al., 2003). In addition to this, ecosystem quality received the least variability from each aeration strategy in the underlying LCIA analysis (Singh et al., 2020). Singh et al. (2020) attributed this to the negligible difference in removal performance of heavy metals by each aeration strategy that would ultimately be introduced to the soil in sludge or water through the effluent.

3.3. Treatment performance contribution

By calculating the TFSI score for individual pollutants, it is possible to observe which strategy is most sustainable specific for each. For instance, Fig. 5 shows that CA I is the most sustainable strategy for TP removal with a TFSI score of 0.61 Pt/m^3. In comparison, the IA strategies range between 0.65 and 0.74 Pt/m^3 while the remaining CA strategies ranged between 0.79 and 0.80 Pt/m^3. Sustainability was observed to decrease with increasing non-aerated period in IA strategies when considering TP removal, which is likely attributed to the greater release of phosphorus with increasing anoxic period (Singh et al., 2017a). Of the CA strategies, CA III was observed to be the least sustainable for the removal of this parameter.

When considering the sustainability of COD removal, CA I and CA III demonstrated very similar scores (0.76–0.77 Pt/m^3) despite the underlying removal efficiencies differing greatly with effluent concentrations of 85 mg/L and 25 mg/L respectively (Singh et al., 2017b). With CA I not achieving its effluent limits of 50 mg/L (Ministry of Environment, Forest and Climate Change, 2015), this promotes the need to further investigate the allocated weightings for each indicator for better representation. The sustainability of BOD removal followed a similar trend across aeration strategies, however in this case CA III outperformed CA I by a slightly larger margin with scores of 0.73 Pt/m^3 and 0.77 Pt/m^3 respectively. In terms of TSS, little variation was observed within CA and IA types with ranges shown as 0.75–0.79 Pt/m^3 and 0.49–0.53 Pt/m^3, respectively.

For TN removal, the IA strategies again offered the most sustainable removal with TFSI scores between 0.49 and 0.53 Pt/m^3. Within the CA

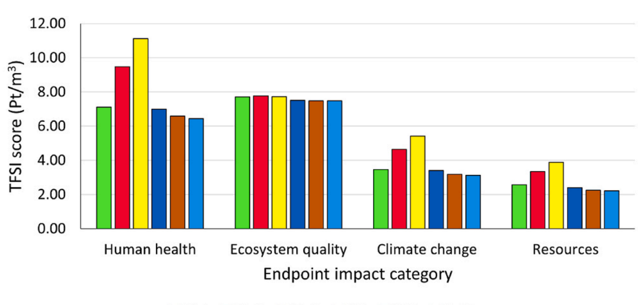

Fig. 4. TFSI scores for each endpoint category under alternative aeration regimes.

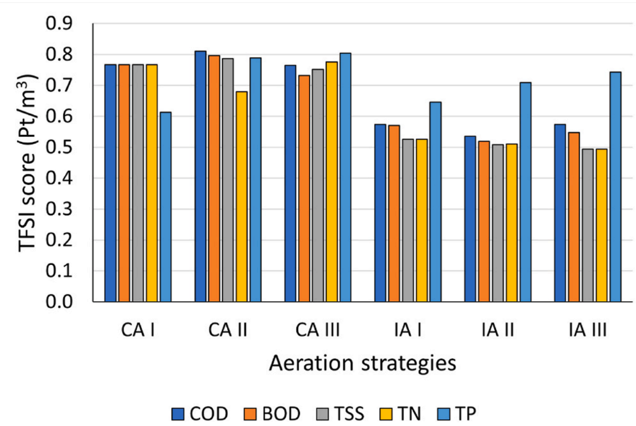

Fig. 5. TFSI scores for each aeration strategy with respect to each pollutant considered.

strategies, CA II afforded the greatest sustainability at 0.68 Pt/m^3 which was a considerable margin compared to the remaining strategies (0.77–0.78 Pt/m^3). This was due to the similar TN removal of both CA II and CA III strategies reported by Singh et al. (2017b), but with the former requiring a reduced aeration rate due to the occurrence of SND (Singh et al., 2016).

In summary, these results find IA II to be the most sustainable across the range of pollutants excluding one. For TP specific removal, the results suggest CA I to be the most sustainable approach with IA I the best option from the IA strategies for this parameter. This common disparity between CA and IA types across most pollutants demonstrates the advantage of IA strategies to offer a similar or better performance despite the reduced aeration period and rate.

4. Discussion

The results of the present work have identified IA strategies to offer greater sustainability than CA strategies when considered from a techno-eco-efficient perspective. Further focus into the potential of IA in biological wastewater treatment is warranted if the water sector is to achieve net zero (Water UK, 2022). However, these results are drawn under a few caveats that are here discussed.

Technical performance plays a critical role in future-proofing during optioneering of wastewater treatment strategies (Kamble et al., 2019). In their assessment of the eco-efficiency of 6 alternative WWTPs, Kamble et al. (2019) made the case that while more economical options existed, these would be redundant if they were unable to achieve sufficient treatment under tightening effluent targets. While the current work has shown IA strategies to be more favourable from the perspective of sustainability, it is worth noting that CA III offered the highest quality effluent albeit at the cost of reduced eco-efficiency. Should effluent limits be further tightened, it may become the case that CA III is the only viable strategy regardless of environmental and economic performance. In contrast, other strategies that fail to meet regulatory obligations of fulfilment will provoke not only their own environmental burden through increased water pollution, but also additional economic costs associated with the legal implications (Starkl et al., 2018).

A further caveat is that nitrous oxide (N_2O) emissions were not accounted for within the TFSI, having not been reported in the underlying work (Singh et al., 2020). These will be expected to weigh heavily on the LCIA of the IA strategies (Scheehle and Kruger, 2006). N_2O has a global warming potential 298 times higher than CO_2 and is the highest contributor to O_3-depletion of all the greenhouse gases (GHGs; Ravishankara et al., 2009). A study by Parravicini et al. (2016) found N_2O emissions from the activated sludge reactor to account for as much as 43% of the plants GHGs. The primary pathway for these emissions in biological wastewater treatment is through the exposure of ammonia-oxidizing bacteria (AOBs) to the anoxic conditions of the oxic-anoxic cycling (Ahn et al., 2010). This is particularly problematic for IFAS reactors under IA that host particularly high concentrations of AOB biomass (Singh and Kazmi, 2016). As such, the environmental performance and consequently the overall sustainability profile of the IA strategies are likely to be considerably diminished.

While the present work has investigated the increased sustainability that may be realised by alternative aeration strategies, there are other ways that sustainability gains may be made during oxygen delivery. Henriques and Catarino (2017) discussed a series of other steps that could be taken to improve the sustainability of aerated WWTPs including improved housekeeping, process changes and equipment modifications. Particular emphasis was given to the use of fine bubble diffusers. While the investigated IFAS in the present work already employs fine bubble diffusion, the considerable increase in efficiency that they offer deserve emphasis. Moga et al. (2019) suggested potential energy reductions of 20% in AS plants and 40% in IFAS-style plants were possible at a bubble size of 1 mm when compared to the use of conventional coarse options. Other recent work has found that these efficiency gains can be amplified as these bubble sizes are further reduced to 0.05 mm (Boltinescu et al., 2022), however additional consideration will be need to be given to the detriment of clogging which is prone in diffusers of finer bubble size (Drewnowski et al., 2019). Regardless, the performance of fine-bubble aerations systems is continuing to improve oxygen transfer efficiency in wastewater treatment (Behnisch et al., 2020), and remains a valuable tool in the development of sustainable oxygen delivery.

Automated control systems provide a further way in which sustainability may be improved during aeration. Irrespective of the aeration strategy employed, minimizing oxygen delivery to only provide the allocated concentration should be a priority when enhancing sustainability. Khatri et al. (2020) suggested possible savings of >66% when implementing DO-feedback control in an AS plant under CA. Control systems that adjust the rate of aeration according to influent or effluent characteristics such as ammonia-based aeration control (ABAC) have also been shown to offer substantial energy savings as well as improved performance of targeted pollutants. For example, Rieger et al. (2012) reported energy savings between 16 and 20% in three AS plants with up to 40% improved TN removal when using ABAC with dynamic simulation. Várhelyi et al. (2019) demonstrated energy savings of up to 45% were possible with ABAC with improved TN removal compared to fixed aeration, while other work found improved nitrification but with lesser energy savings at ~9% (Medinilla et al., 2020). Further work is warranted to evaluate the sustainability of the ABAC approach as a distinct aeration strategy to be compared with more conventional CA and IA approaches in the IFAS system. It is recommended that any such analysis should be holistic to account for associated issues that have recently been reported with the ABAC aeration strategy such as reduced settling performance (Stewart et al., 2022) and increased N_2O production (Boiocchi and Bertanza, 2022). Regardless, this approach continues to gain popularity with increasingly intelligent control models being used to further optimize its efficiency (Icke et al., 2020; Newhart et al., 2020).

5. Conclusions

The present work has evaluated and compared the sustainability of 6 aeration strategies (3 CA and 3 IA). This has been achieved by extending the commonly used EEI (EN ISO 14045: 2012) to a novel TFSI that incorporates a third factor. While the EEI considers both the economic and environmental burden of clean wastewater production, the TFSI includes an additional indicator that reflects the general treatment performance of each investigated strategy. The validity of the TFSI is confirmed by contrasting the scores of each index for each strategy. TFSI scores are then calculated at the individual midpoint and endpoint categories, as well as per individual pollutant.

The study has found IA to be an overall more sustainable and carbon-efficient operational strategy when compared to CA in an urban wastewater treatment system, with little difference observed between each of the different anoxic cycle portions. While CA at a higher DO setpoint is known to offer the highest treatment performance, this is outweighed by the environmental and economic costs incurred to maintain it. Conversely, while CA at the lowest DO setpoint demonstrated the greatest eco-efficiency, its adverse effect on the treatment performance invalidated this as a viable approach. These results added credence to the need for technical performance to be considered in conjunction with other sustainability indicators when assessing operational strategies in wastewater treatment.

Further work should now look to incorporate the environmental impacts associated with N_2O emissions that each strategy may generate, as this is likely to influence the results. Furthermore, the analysis should be extended to evaluate the sustainability of providing oxygen by way of automated-control as this may yield further efficiency gains. It is hoped the results of this study will aid decision makers in achieving more sustainable, and perhaps net zero infrastructure during urban development. The generic methodology and the developed integrated evaluation framework can be applied to overall treatment schemes, let alone biological secondary treatments.

CRediT authorship contribution statement

David Pryce: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft. **Zoran Kapelan:** Visualization, Validation, Supervision. **Fayyaz A. Memon:** Visualization, Validation, Supervision.

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.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work was funded by the Engineering and Physical Sciences Research Council (EPSRC) under the STREAM Centre for Doctoral Training programme (EP/L015412/1). For the purpose of open access, the author has applied a ‘Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising’ (where permitted by UKRI, ‘Open Government Licence’ or ‘Creative Commons Attribution No-derivatives (CC BY-ND) licence may be stated instead).

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