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# Economic evaluation of a small wastewater treatment plant under different design and operation scenarios by life cycle costing

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ABSTRACT

High-performance wastewater treatment technologies suited to the urban environment remain largely inaccessible to developing countries due to financial constraints. Instead, inadequate technologies are being used that adversely affect the quality of water resources and limit their sustainability. One high performing technology that offers possible solution is a packaged version of the integrated fixed-film activated sludge (IFAS) system consisting of a 20 $m^3$ aerobic reactor and a 4.2 $m^3$ settlement tank. The present work has investigated aspects of this typically-expensive solution that can be economized to improve its uptake in these countries. To achieve this a life cycle cost analysis (LCCA) was performed and potential savings identified. The results obtained show that the life cycle cost is \$0.31/$m^3$ and that costs primarily occurred at the construction stage (11.9%) and the operation and maintenance stage (88.1%) with negligible disposal costs. A reduction of up to 42.4% in construction costs were shown to be accessible by adopting other materials such as high-density polyethylene (HDPE) or to a lesser extent glass-fibre reinforced polymer (GFRP). The greatest single cost in the life cycle was found to be incurred by aeration (48.9%), requiring expenditure of \$0.15/$m^3$, however the use of intermittent aeration (IA) could reduce this further to \$0.08/$m^3$. Further work is suggested to investigate the broader sustainability of the different aeration strategies in light of these economic results.

## 1. Introduction

The risk of water scarcity in rapidly developing countries such as India is becoming increasingly alarming due to the combined effects of a fast-growing population and a rapidly-diminishing quality of available water (Mishra et al., 2021; Singh and Mahanta 2021). Adequate wastewater management continues to fall short, often as a result of the limited available financial resources inherent in these countries (Starkl et al., 2013a; Chatterjee et al., 2016; Bayu et al., 2020). This issue is particularly prevalent in areas of limited land availability such as the urban environment (Larsen et al., 2016). Technologies that are typically more cost-effective such as constructed wetlands and waste stabilisation ponds can be circumstantially-void in these areas due to the large land allocation they require (Starkl et al., 2013b). Instead, a greater reliance is placed on household level septic tanks that remain unfit for purpose under such high urban densities (Dasgupta et al., 2021). Even at the community level, technologies such as the upflow anaerobic sludge blanket (UASB) system continue to be favoured in developing countries due to the low energy demand, despite requiring a large footprint and often failing to meet effluent limits (Makwana and Ahammed 2017; Bassi et al., 2022; Rathore et al., 2022). More popular is the activated sludge (AS) process and sequencing batch reactor (SBR) technology that together account for almost 50% of the municipal technologies currently being used in India (Bassi et al., 2022). While they offer a greater treatment efficacy than the USAB, their throughput remains limited by their large footprint requirements (Rathore et al., 2022). As such, high-performing technologies are required that can provide sufficient wastewater treatment to meet regulatory targets, but in a smaller footprint more suited for the urban environment. Unfortunately, these technologies most often incur the greatest costs (Starkl et al., 2018), thus limiting their wide-spread adoption in less-affluent countries and the environmental benefits they afford.

One technology that is capable of affording high treatment performance in a reduced footprint is the integrated fixed film activated sludge (IFAS) system (Rosso et al., 2011). Its advantage is attributed to its integration of both fixed media and sludge recycle stream to increase the amount of functional biomass within the reactor (Ekama 2015). The last decade has seen extensive investigation of the potential of a packaged

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IFAS system in India during trials, yielding strong results for pollution mitigation under different configurations (Singh and Kazmi 2016; Singh et al. 2016, 2017a). However, from an economic perspective this advantage is a key limitation of this technology with much of the biomass requiring oxygen as the electron donor during pollution degradation (Bai et al., 2016). Aeration must therefore be provided at higher rates than required by technologies that utilize lower biomass such as AS systems or biofilters (Rosso et al., 2011). With aeration being a critical cost in wastewater treatment due to the high energy consumption it demands (Mamais et al., 2015), this makes the IFAS an expensive treatment option.

In the present work a case study was undertaken to investigate the potential for cost reductions in several key areas of a decentralized IFAS system that is a promising but relatively expensive urban wastewater treatment solution. Total costs incurred during the technologies service life were assessed by way of a life cycle cost analysis (LCCA). This method is commonly utilized as a means to evaluate and model the financial burden of a technology at its different life stages (Ilyas et al., 2021), and has proven useful during the early stages of wastewater treatment design (Harris et al., 2021). By doing so, it is possible to investigate and compare the influence of alternative designs, configurations and operation scenarios on a system's economy.

For the present work, three aspects of the IFAS system design and operation were costed. First, the relative costs incurred by several alternative materials that may be used during the system's construction phase in place of the currently-used austenitic stainless steel (SS) were considered. These include mild steel (MS), glass-fibre reinforced polymer (GFRP), high-density polyethylene (HDPE) and reinforced concrete cement (RCC). By way of LCCA, Younis et al. (2020) compared several alternative materials that could be used to reinforce concrete in a water chlorination tank, identifying GFRP to be the most economical option over longer service life. Nagels et al. (2022) performed a LCCA to compare the total economic costs of using different steel grades in wastewater treatment roles, identifying a greater economy of duplex steel in the most corrosive environments.

Second, the economic costs of enhancing the system configuration for improved total nitrogen (TN) removal have been evaluated. Recent modelling work by the authors has shown that TN removal can be enhanced in the investigated IFAS system when a post-anoxic tank is included at a 5:1 (aerobic:anoxic) volume ratio in the system (Pryce et al. unpublished). Providing this additional treatment is becoming increasingly necessitated with effluent limits continuing to tighten (Schellenberg et al., 2020; Tang et al., 2022; Xie et al., 2021). As such, understanding the financial implications of providing this higher level of treatment may identify opportunities for greater cost efficiency. For example, by way of LCCA, Morelli et al. (2018) identified possible cost savings of up to 15% were possible in an AS system when configurational changes were made during upgrade for nutrient removal. Similarly, Awad et al. (2019) showed that the costs of upgrading an AS plant to reuse standard in Egypt could lead to positive equity over a long period.

Finally, the economic costs of various aeration strategies that have been utilized with the IFAS system were investigated. The plight for increased efficiency to reduce these costs has led to an array of aeration strategies being investigated including varying intermittent aeration (IA) cycles and different dissolved oxygen (DO) set points in continuous aeration (CA) that will each incur their own economic burden (Singh et al. 2016, 2017a). While previous work has investigated the potential economic gains of improving aeration efficiency through the use of different diffuser types (Viholainen et al., 2015), different blowers and on-line instrumentation (Brischke and Eschborn 2016), and different delivery systems, i.e. blast or surface (Liai et al., 2017), no work appears to have evaluated the total investment costs incurred by each of the alternative aeration strategies. Understanding these relative costs will better inform decision-making processes during both technology optioneering and operational strategizing and may offer significant economic gains in urban wastewater management.

## 2. Method

### 2.1. Study system

The system under study is a package IFAS reactor that has been trialled in India treating municipal wastewater (Singh and Kazmi 2016, 2017a). Its main components are shown in Fig. 1 and include an influent pipe with a 0.75 kW centrifugal pump to control the influent flow rate ($Q = 69.6\ m^3/d$). This leads into the 20 $m^3$ aerobic reactor that contains 64 Cleartec Biotextil® media sheets (2.7 m × 0.96 m), four Aerostrip® T1.5-EU-18 air diffusers and an SS media frame. Depending on configuration, an anoxic tank may be included following the aerobic tank for improved denitrification. Recent work from the authors has found 4 $m^3$ to be the most efficient anoxic volume for this system (Pryce et al. unpublished). This feeds into a 4.2 $m^3$ circular settlement tank with a conical base that has three outputs including the waste activated sludge (WAS) point, the effluent point and the recycle activated sludge (RAS) stream. Both the WAS and RAS point have flow control valves while the RAS stream has a 0.95 centrifugal pump to control the flow rate (~1.25Q). Inter-connecting pipes are of SS construction while the influent and effluent pipes are of HDPE construction. The activated sludge is wasted at a rate of 1.1 $m^3/d$ (Singh and Kazmi 2016). Air is provided by a commercial blower at varying rates depending on the aeration strategy, but as an indication 50 $m^3/d$ provides a dissolved oxygen (DO) concentration of 2.5–3.0 mg/L (Singh et al., 2017b). The operational settings are governed by a central control panel. System components are illustrated in Fig. 1.

### 2.2. Goal and scope descriptions

The goal of the present work was to calculate the total life cycle costs of the IFAS system under alternative scenarios of construction, configuration and operation. In terms of construction, the IFAS system was costed under five tank material scenarios including SS, MS, GFRP, HDPE and RCC. Material quantities for these scenarios have been calculated in previous work (Pryce et al., 2021). For operation, life cycle costs were considered for the IFAS system under 7 aeration strategies that have previously been investigated (Singh et al., 2016; 2017a, Pryce et al. unpublished). These are displayed in Table 1.

System cost components included in the present LCCA are depicted in Fig. 2. In brief, these costs consider tank materials, each component cost (pipes, valves, influent and sludge pumps, control panel, air pump), specific components unobtainable in India (Aerostrip® T1.5-EU-18 type diffusers and Jäger Cleartec® Biotextil Media sheets) including their import costs, energy costs for operation (aeration and sewage pumping), water costs for maintenance, skilled and unskilled labour costs across life cycle, and equipment hire costs for maintenance (crane) and disposal (truck-mounted crane to transport). A 15-year service life was considered for the pumps, pipes, tanks and other technical parts in line with previous life cycle analyses (LCAs) investigating wastewater treatment systems (Vlasopoulos et al., 2006). Maintenance was considered to occur every 6 months whereby the media frame is lifted outside of the IFAS reactor and hosed with tap water (0.5 $m^3$ per event) to remove sludge build-up that may hinder effective system function.

The functional unit (FU) is considered as 1 $m^3$ being the most commonly used LCAs of wastewater treatment systems (Corominas et al., 2013).

### 2.3. Costing assessment

In pricing all materials and components, an average is taken of the costs from 3 different suppliers for each (IndiaMart 2022). The process for calculating tank costs differed between materials due to available pricing. Prices for stainless steel 316 L and mild steel are given per kg,

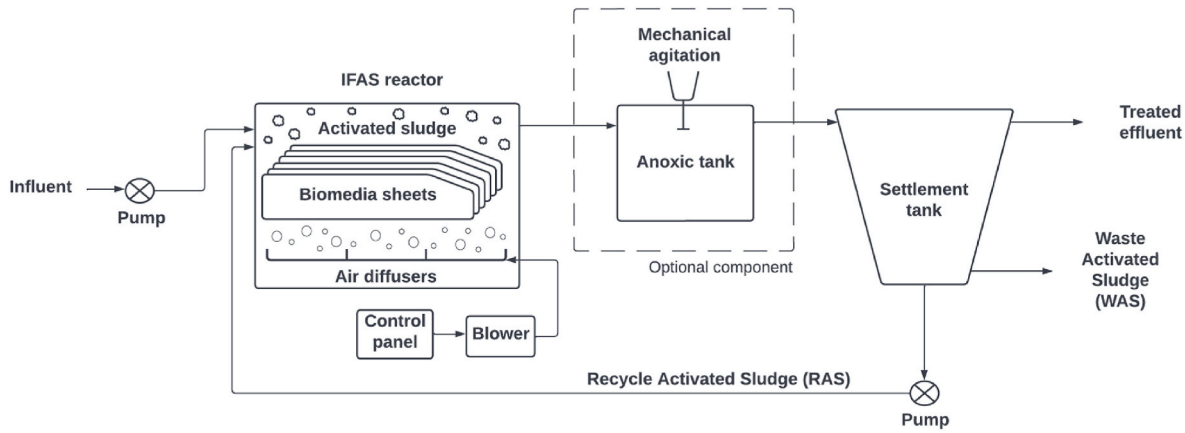


**Fig. 1.** IFAS system diagram.

**Table 1**
Aeration strategies described.

| Aeration strategy | Description | Reference |
|---|---|---|
| CA I | Continuous aeration delivered at the necessary rate to provide a dissolved oxygen concentration of 0.5 mg/L | Singh et al. (2016) |
| CA II | Continuous aeration delivered at the necessary rate to provide a dissolved oxygen concentration of 2.5 mg/L | Singh et al. (2016) |
| CA III | Continuous aeration delivered at the necessary rate to provide a dissolved oxygen concentration of 4.5 mg/L | Singh et al. (2016) |
| CA IV | Continuous aeration delivered at the necessary rate to provide a dissolved oxygen concentration of 3.5 mg/L | Pryce et al. (unpublished) |
| IA I | Aeration provided intermittently in a cycle of 2.5 h on and 0.5 h off at the necessary rate to provide a dissolved oxygen concentration between 2.5 and 3.0 mg/L during the aerated period | Singh et al. (2017a) |
| IA II | Aeration provided intermittently in a cycle of 2.0 h on and 1.0 h off at the necessary rate to provide a dissolved oxygen concentration between 2.5 and 3.0 mg/L during the aerated period | Singh et al. (2017a) |
| IA III | Aeration provided intermittently in a cycle of 1.5 h on and 0.5 h off at the necessary rate to provide a dissolved oxygen concentration between 2.5 and 3.0 mg/L during the aerated period | Singh et al. (2017a) |

and the weights of each material for the IFAS and settlement tank are taken from Pryce et al. (2021). The weights required for the 4 $m^3$ anoxic tank are calculated in the same way and displayed in Section S1 and Table S1 of the supplementary material. Costs for the remaining materials (GFRP, HDPE and RCC) are taken per L of tank required as offered by the retailers (IndiaMart 2022) and displayed in Table S2 of the supplementary material.

The removable media frame is known to weigh 210 kg according to manufacturer specifications. Total costs of the Cleartec Biotextil® media as provided by the UK supplier have been included for the full compliment of 64 sheets (2.7 m × 0.96 m), while the costs of the four Aerostrip® T1.5-EU-18 air diffusers together from the same UK supplier are also included. Import costs for the necessary 64 media sheets and 4 diffusers for one IFAS from the UK suppliers to Mumbai in a standard 1.2 m × 1.0 m x 2.0 m pallet are considered as $715.14 as quoted by the UK supplier. Capital costs for system components can be found in Table S3 of the supplementary material.

Minimum wage of skilled worker in India in 2022 is taken as 950 INR/d, while unskilled workers are taken as 400 INR/d in line with previous projections (Sayed and Sawant 2015). It is assumed that one skilled and one unskilled worker are required for one day to construct each tank, while only one skilled worker is required for one day to construct the media frame. All labour costs during the construction stage are incorporated into the costs of tank construction. The INR:USD exchange rate is taken as 0.0131 USD (Exchange Rates, 2022).

In terms of operation and maintenance (O&M), these costs are displayed in Table S4 of the supplementary material. The operational costs consider the energy costs of the anoxic tank mixer (6 kW) where included, Influent and RAS pumps, and aeration pump under each aeration strategy. The maintenance costs account for the costs of crane and driver hire to lift the media frame for periodic hosing (every 6 months according to manufacturer's specification) for half a day. The cost of hose water is not included as the reuse of treated effluent is assumed, however the costs of wasted sludge disposal are included within the maintenance costs. The sludge disposal costs are based on the assumption that a 3.5 $m^3$ capacity vacuum truck collects the waste sludge by schedule every 3 days (1.1 $m^3$ wasted sludge per day) at a cost of $12 per trip as has been reported in the Indian urban centres of Wai and Sinnar (Mehta et al., 2019). The cost of labour for maintenance is also included assuming one skilled worker is employed full time to monitor, operate and maintain this and 4 other similar decentralized, sewage treatment plants, i.e 1/5th of daily rate.

To consider the disposal (decommissioning) costs, the cost of a transport truck with mounted crane for 1 day as well as the cost of labour to include a skilled and unskilled worker also for a day are accounted for. While the cost of disposing of the removed system by open dumping could be taken as $5.17/tonne (Mehta et al., 2018), these costs were excluded based on the assumption decommissioned equipment would be repurposed where possible. These costs are displayed in Table S5 of the supplementary material.

Costs relating to the incorporation of an anoxic tank + agitator including capital and O&M costs are not included in the primary life cycle costs but as a separate analysis. No additional decommissioning costs are considered to be incurred for the anoxic tank or agitator.

### 2.4. Life cycle cost model development

For the calculation of the total life cycle cost (LCC) of the IFAS under each scenario, a model previously used by Younis et al. (2018) was utilized as shown in Equation (1).

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

This model calculates the net present value (NPV) of all costs incurred throughout the service life ($t$) accounting for value change each year due to the real discount rate ($r$). Thus, the costs incurred each year

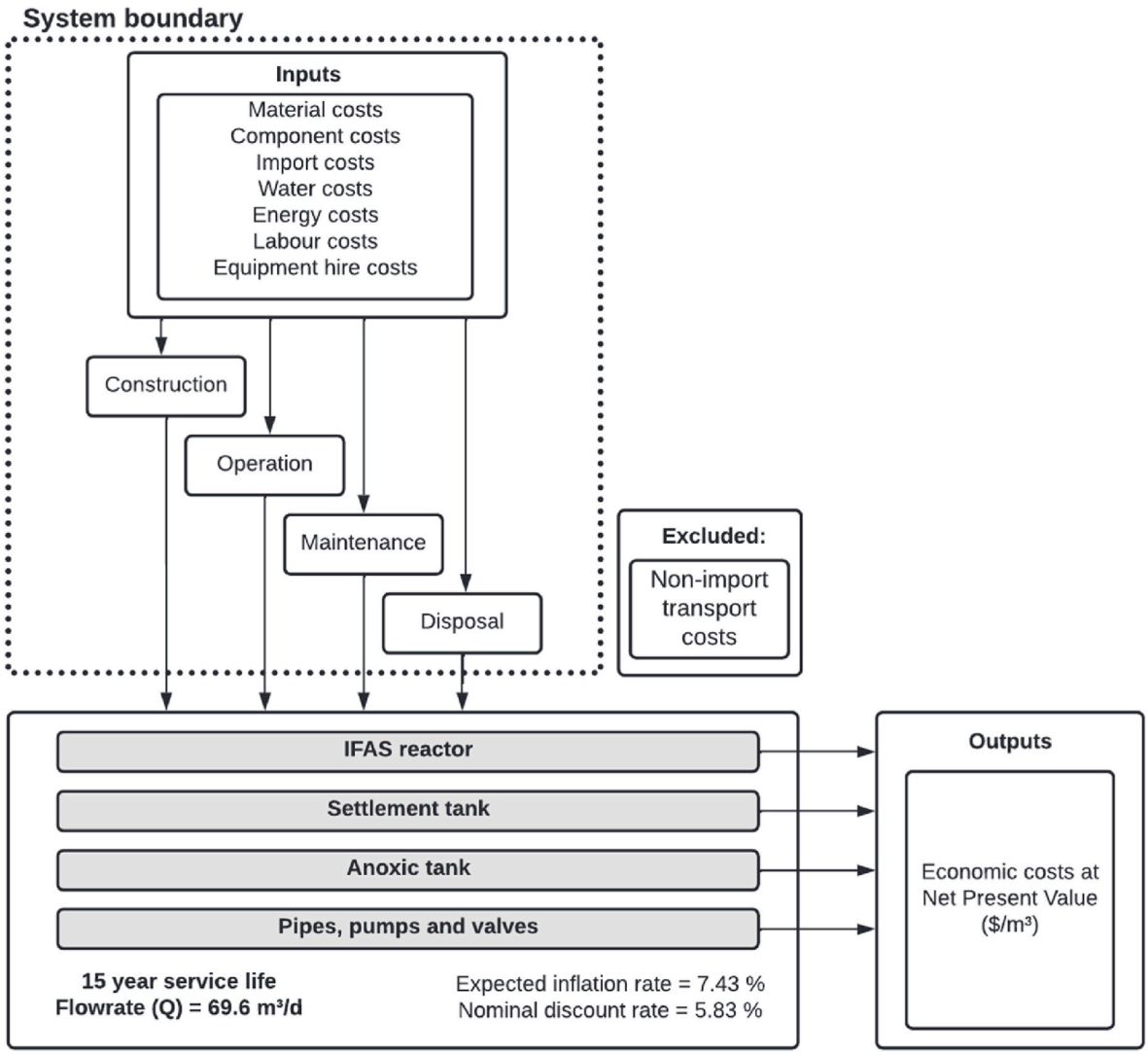


**Fig. 2.** System boundary of the LCCA.

($C_t$) will differ with the total life cycle cost being the sum of each year (Younis et al., 2018). Calculation of the NPV is a critical step in economic analysis as expected inflation ($i$) is often overlooked in construction project bugets (Musarat et al., 2021).

In order to determine the NPV of the total LCC, $r$ is calculated as follows (Jawad and Ozbay 2006):

$$Real\ discount\ rate, r = \frac{i-d}{1+d} \tag{2}$$

As shown in Equation (2), $r$ is a function of $i$ and the bank interest rates ($d$). In the present work, $i$ was given as 7.43% in line with the average consumer price index (CPI) inflation rate of India in years 1960–2020 (World Bank Data – inflation, 2022). Based on an average of years 1978–2020 for India, $d$ was taken as 5.83% (World Bank Data – real interest rate, 2022).

For the calculation of the costs each year, the following equation is used:

$$Cost\ incurred\ at\ year\ t, C_t = C_{CAP} + C_{O\&M} + C_D \tag{3}$$

For Equation (3), the necessary elements are included at the appropriate $t$. For example, the capital costs ($C_{CAP}$) are included only when $t = 0$, while the disposal or decommissioning costs ($C_D$) are only included in the final year of the service life when $t = 14$. In contrast, the operation and maintenance costs ($C_{O\&M}$) are included every year as annual costs.$C_{CAP}$ are represented by the following equation:

$$C_{CAP}(\$/m^3) = C_T + C_{IC} + C_{CI} + C_{EC} \tag{4}$$

$C_{CAP}$ considers the cost of all tanks ($C_T$), cost of internal components ($C_{IC}$), cost of component import ($C_{CI}$) regarding diffusers and media, cost of locally-sourced external components ($C_{EC}$) including piping, influent and sludge recycle pumps, air pump and control panel, agitator and valves.

To calculate $C_{O\&M}$, the following equation is used:

$$C_{O\&M}(\$/m^3) = C_{OA} + C_{OP} + C_{OAA} + C_{CH} + C_{LOM} + C_{SD} + C_H \tag{5}$$

Here, $C_{O\&M}$ account for cost of energy for aeration ($C_{OA}$), the cost of both sewage pumps ($C_{OP}$), cost of energy for anoxic tank agitation ($C_{OAA}$) where applicable, cost of labour for operation and maintenance ($C_{LOM}$), cost for sludge disposal ($C_{SD}$), and cost of crane hire for lifting media during bi-annual maintenance event ($C_H$).

The end-of-life (EOL) disposal costs ($C_D$) are calculated as follows:

$$C_D(\$/m^3) = C_{TCH} + C_{LD} \tag{6}$$

These costs include the cost of truck-based crane hire ($C_{TCH}$) to load and transport the system to landfill or recycle. It is assumed that no costs are incurred to dispose of the system at these destinations. Also included in $C_D$ are the cost of labour for decommissioning and disposal ($C_{LD}$).

Finally, a local sensitivity analysis (LSA) was also performed to identify model parameters most influential to the system life cycle costs with details available in Section S3 of the Supplementary Material. Both the LCCA and LSA were performed using Microsoft Excel (2021).

## 3. Results and discussion

### 3.1. Evaluation of the total life cycle costs of the IFAS system

Results of the LCCA are considered for a continuous aeration IFAS system of SS construction without an additional anoxic tank and with a DO setting of 4.5 mg/L, whereby the total life cycle costs are realised as \$0.31/m$^3$. Construction was shown to incur 11.9% of the overall cost at \$0.04/m$^3$, while the EOL costs were found to be negligible at <\$0.01/m$^3$ due to the small scale of the investigated plant. The greatest cost was observed during the O&M stage at \$0.27/m$^3$ and was responsible for 88.1% of the total costs, with operation and maintenance accounting for 62.9% and 26.1% respectively as shown in Fig. 3a. This was mainly due to aeration as shown in Fig. 3b, which was found to incur the greatest portion of the total life cycle costs as would be expected (Drewnowski et al., 2019). Aeration accounted for 48.9% of the total life costs which translated as \$0.15/m$^3$. In contrast, the combined pumping costs for the influent and RAS streams which constituted the rest of the operational costs were only \$0.04/m$^3$ which accounted for the second largest portion of the costs at 14.3%. Maintenance costs were responsible for 24.9% of the total costs at \$0.08/m$^3$, with this mostly attributed to the costs of sludge disposal (13.6%) and labour required for O&M (11.3%).

These results further highlighted the high energy demand of this technology, with total energy costs accounting for 63.2% of the total costs at \$0.19/m$^3$. With energy demanding such a high portion of the total costs, this poses further problems due to the vulnerability of the technology to increasing energy prices. This was further reinforced by the sensitivity analysis which showed the cost of energy for aeration ($C_{OA}$) to be the most influential parameter after system longevity as shown in Fig. S2 of the Supplementary Material. Electricity prices are sensitive to multiple factors such as utility privatization (Pollitt 2019; Johnstone and Havyatt 2021), regulation and liberalization (da Silva and Cerqueira 2017), renewable energy uptake (Adom et al., 2018; Wen et al., 2022), clean energy initiatives (Wong and Zhang 2022), fossil fuel price fluctuations (Liu et al., 2020), and geopolitics (Escribano 2019; Hickey et al., 2021; Hosseini 2022; Khan 2022). Any increase in prices that may occur for these reasons will increase the life cycle costs of the IFAS disproportionately compared to more passive technologies. This will need to be accounted for when considering the economic profile of the technology throughout its service life.

### 3.2. Cost comparison of the IFAS system under different material scenarios

The construction phase was shown to incur 11.9% of the total life cycle costs with a capex of \$13,930, however the results of the present work suggest this expenditure may be reduced considerably by the use of alternative materials. For example, the use of MS in place of SS could see a three-fold expense reduction from \$6188 to \$2,005, while replacement for GFRP or RCC could see costs reduced by an order of magnitude to \$398 and \$519 respectively. As shown in Fig. 4, the cheapest material was found to be HDPE which would incur a cost of only \$277 to construct the tanks and would reduce the overall capex costs by \$5910 (42.4%) compared to the SS scenario.

While the value of SS may increase at an extended design service life perhaps due to a higher durability than other materials (Nagels et al., 2022), it can be concluded that for a typical service life of 15 years each of the other materials will be fit for purpose but at a highly reduced outlay. Besides, other work has found GFRP to be a more favourable material than SS in terms of mechanical properties particularly in corrosive environments (Kumarasamy et al., 2020), while the inert characteristics of plastic polymers such as HDPE are gaining favourability over steel and concrete for piping and small wastewater treatment plants (Seibi and Pervez 2006; Machado et al., 2007; MortezaNia and Othman 2012).

Recent work has indicated a similar trend to the present results when considering the environmental impact incurred by each of the investigated materials in a small wastewater treatment plant role (Pryce et al., 2021). In fact, the only difference observed is that GFRP was shown to incur the second greatest environmental impact in the previous work which is contrast to the present work where it is the second most favourable material from an economic standpoint. While GFRP typically incurs a greater initial outlay compared to SS (Berg et al., 2006), this has not been found to be the case in the present work. This is likely due to the reduced costs associated with using pre-fabricated panels compared to whole tank construction by more expensive and laborious manufacturing techniques. A further explanation may be the lower quantity requirements compared in small-scale wastewater containment compared to other applications such as structural reinforcement (Eamon et al., 2012).

The present work therefore supports the previous LCA results and postulate that the IFAS can realize not only increased environmental sensitivity but also greater economy by adopting alternative materials in

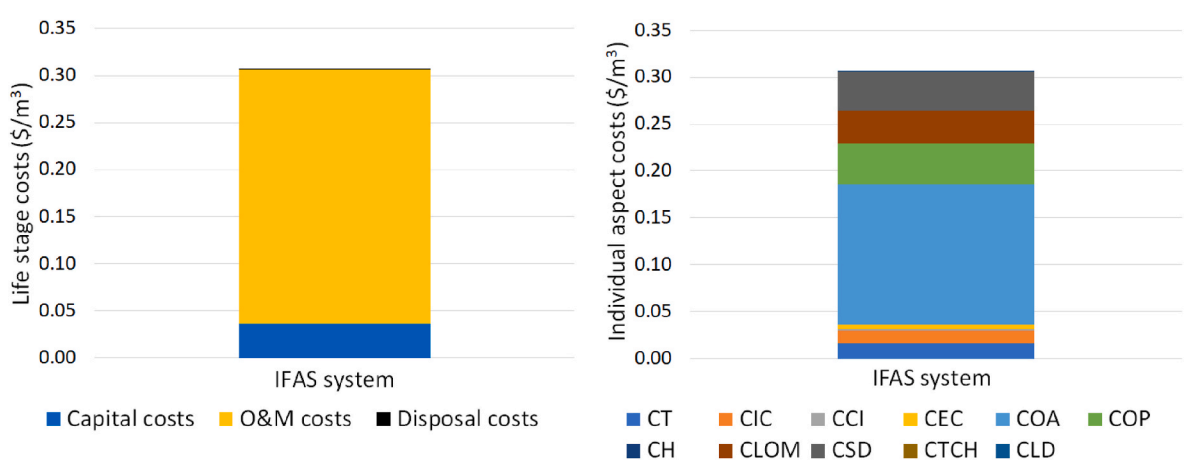


**Fig. 3.** a. Costs incurred at each life stage for the IFAS system and b. Individual aspect costs during life cycle for the IFAS system. Considered specifications for each = SS construction, CA, DO 4.5 mg/L. CT = Cost of tanks, CIC = Cost of internal components, CCI = Cost of component import, CEC = Cost of external components, COA = Cost of energy for aeration, COP = Cost of energy for pumps, CH = Cost of crane hire, CLOM = Cost of labour for O&M, CSD = Cost of sludge disposal, CTCH = Cost of truck mounted crane hire for system disposal, CLD = Cost of labour for disposal.

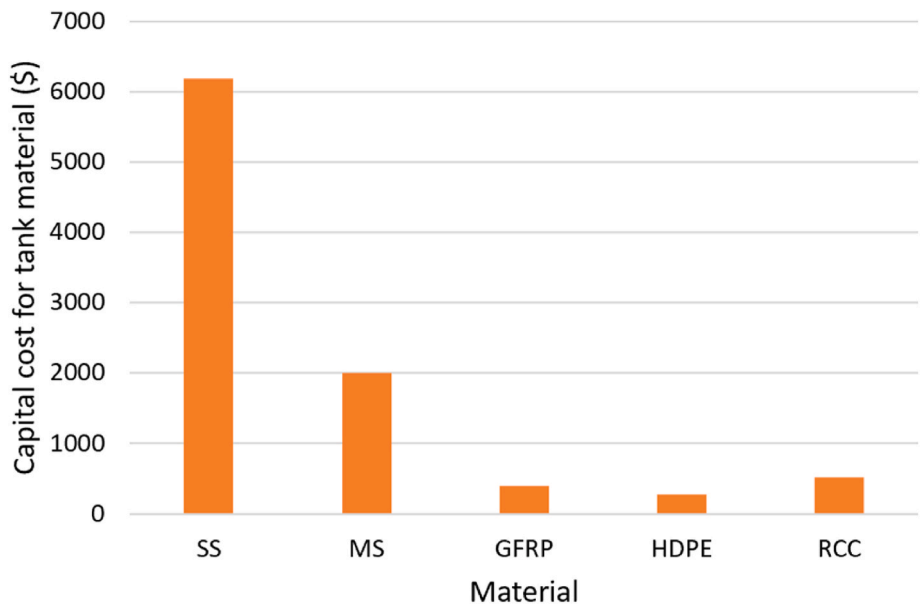


**Fig. 4.** Cost comparison of alternative tank construction materials. SS = Stainless steel, MS = Mild steel, GFRP = Glass fibre reinforced polymer, HDPE = High density polyethylene and RCC = Reinforced concrete cement.

its construction.

### 3.3. Evaluating the costs of enhanced TN removal in the IFAS system

The present work found the inclusion of a post-anoxic tank in an SS IFAS configuration to incur an increase of $17,710 in the total life cycle costs. The operational phase was seen to account for 86.7% of these additional costs as shown in Fig. 5, while no additional costs were observed during the maintenance and disposal life stages. The increase in OPEX (17.5%) was attributed to the supplementary agitation required to maintain suspension of the mixed liquor suspended solids (MLSS) in lieu of the mixing provided during air diffusion. This is known to be a key issue of IA (Dotro et al., 2011). To a lesser extent, the CAPEX costs observed a 13.0% increase with an additional $2077.56 when using SS as the construction material. However, this additional cost was less substantial when cheaper materials were used. For instance, when MS was utilized the additional expenditure was reduced to $545.21. Even less additional costs were incurred when the remaining materials were used with GFRP, HDPE and RCC demanding an extra $77.69, $57.69 and $97.69 respectively. This adds further emphasis to the economic benefits that may be yielded by adopting less-conventional construction materials in this role (Younis et al., 2020), providing the circular economy is not compromised (Ruiz et al., 2020; Bertino et al., 2021).

With recent work from the authors having demonstrated this configuration to offer the greatest return of investment in terms of treatment performance of key pollution parameters in the investigated IFAS system (Pryce et al. unpublished), future increases in discharge standards may make this approach mandatory. If not, justification for the additional financial undertaking of this enhanced configuration will need to be based on two further analyses. The first will need to consider its value from an environmental perspective, taking into account the trade-off between the environmental gains of reduced effluent emissions

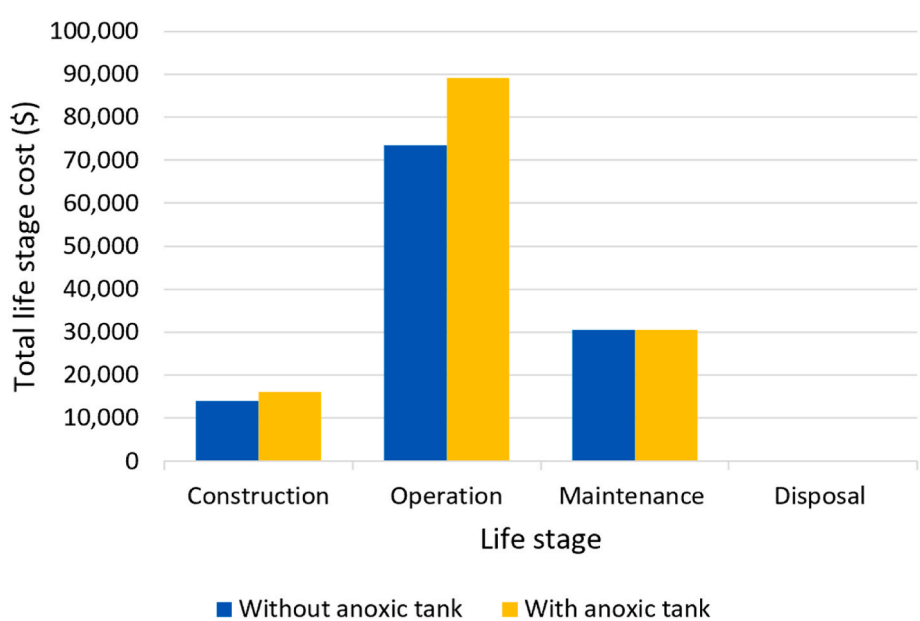


**Fig. 5.** Additional life cycle costs incurred by the incorporation of a 4 $m^3$ anoxic tank in the IFAS system (SS construction, CA, DO 4.5 mg/L).

and the increased environmental burden of the tank construction and energy demand for mechanical agitation. Energy use is known to be a key driver of environmental impact in LCAs (Huijbregts et al., 2010; Polruang et al., 2018; Kamble et al., 2019), while tank construction can also incur significant impact depending on material used (Pryce et al., 2021). Should these impacts outweigh the impacts associated with reduced effluent quality, then the configuration change may be deemed untenable depending on the environmental priorities.

The second analysis that may be used to inform the net value of this configuration change is a cost benefit analysis (CBA). While it is difficult to quantify the environmental benefits of wastewater treatment in economic terms due to a lack of market value, there are a number of ways in which this may be achieved. A classic approach is the contingent valuation method (CVM) that seeks to internalize external benefits by way of willingness-to-pay and willingness-to-accept valuation (del Saz-Salazar et al., 2009; Tziakis et al., 2009; Ginsburgh 2017; Chopra and Das 2019). However, the validity of this approach remains controversial due to the potential for bias, for instance in market participation (Perni et al., 2021). Another method was developed by Molinos-Senante et al. (2010), who used shadow prices for undesirable pollutants in the effluents of different WWTPs as a means to quantify the externalities and value the avoided environmental damage. Other methods include analytical hierarchy process (AHP) that has also been utilized effectively in CBA (Thengane et al., 2014), offering particular advantage when working with both quantitative and qualitative factors.

Perhaps a more appropriate way to investigate the benefits accrued by adopting the investigated configuration in place of these analyses is through use of the eco-efficiency assessment (EEA). This approach incorporates both environmental and economic values taken from LCAs or emergy analyses (EAs) into a single index for comparison (Dong et al., 2017). Due to its ease of use and holistic perspective, this method continues to be widely used in the water sector (Gómez et al., 2018, Abello-Passteni et al., 2020; Mocholi-Arce et al., 2020; Anwar et al., 2021; Revollar et al., 2021).

In any case, the results of this assay provide indication of the economic costs the investigated configuration may incur throughout the technology's lifetime as well as several methods for assessing its internal and external benefits in further work so a CBA can be conducted have been proposed.

### 3.4. Cost comparison of the IFAS system under different aeration strategies

Under CA, a DO setting of 2.5 mg/L was found to incur almost half (47.5%) of the total life cycle costs at \$0.12/m$^3$ which highlighted the importance of this operational parameter in economic analysis. Further investigation was therefore warranted into the economy of the different aeration strategies. As seen in Fig. 6, the results showed that of all strategies, CA III (4.5 mg/L) incurred the greatest cost at \$0.15/m$^3$ as would be expected with this strategy requiring the highest aeration intensity of all alternatives. While CA I (0.5 mg/L) was seen to incur the lowest costs of the CA strategies at \$0.9/m$^3$, this was comparable to each of the IA strategies which showed only little difference between them (\$08–0.9/m$^3$).

In synthesis, CA IV (3.5 mg/L) offers energy cost savings of 11.9% at \$0.13/m$^3$ when compared to the highest DO setpoint, but incurred 5.6% greater costs than at 2.5 mg/L. In contrast, the most economic IA strategy (IA III) yielded possible savings of 45.3% and 37.9% compared to strategies CA III and CA IV respectively. From an economic standpoint, these results suggest IA to offer the greatest economy even compared to CA strategies at the lowest setpoint. While its cost advantage is widely acknowledged, IA is not without its disadvantages such as rapid DO depletion, increased nitrous oxide ($N_2O$) production, enhanced risk of sludge bulking, increased turbidity, and risk of MLSS settling (Dotro et al., 2011; Miao et al., 2022). These challenges will need to be overcome before the financial gains can be achieved.

While these results are informative from an economic perspective, their value in strategizing is performance. In terms of environmental impact, the differences between each strategy will be expected to mirror those of the economic profiles. This is due to the costs, either environmental or economic, being a monotonic function of the energy demand of each strategy. Arguably more important in this instance is the treatment performance that each strategy will afford. For instance, while CA I incurred only \$0.9/m$^3$, the gains of this strategy are negated if it provides insufficient oxygen to support the necessary processes for pollution mitigation (Starkl et al., 2018). As reported in the previous analyses, these strategies do incur significant differences in terms of pollutant removal that will need to be incorporated (Singh et al., 2016). It is therefore recommended that the present results are further integrated with technical performance scores to provide valuable context to implied gains. Additionally, by including the environmental costs of each strategy into the index, a more holistic evaluation of the sustainability of each strategy may be permitted. However, this is outside of the

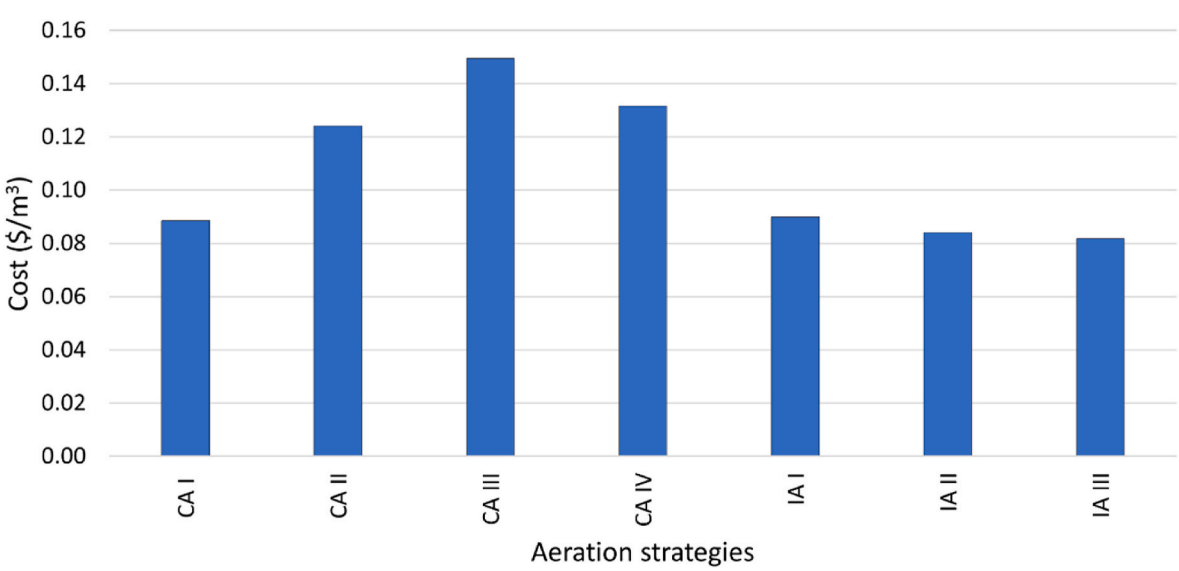


**Fig. 6.** Cost comparison of the different aeration strategies.

scope of the present work. Regardless, the economic profiles of each aeration strategy provided in the current work provides one of the key indicators used in many current sustainability assessment methods (Diaz-Elsayed et al., 2017; Shao et al., 2017; Padilla-Rivera and Güereca 2019; Cossio et al., 2020), and may therefore be of benefit to more detailed analysis.

## 4. Conclusion

Total life cycle costs for a package IFAS system have been calculated accounting for construction costs, ongoing O&M costs and disposal costs. Construction costs have been considered under 5 different material scenarios, while the life cycle costs of 7 different aeration strategies have also been investigated in terms of NPV. Finally, the additional life costs that would be incurred to incorporate a post-anoxic tank with supplementary agitation are calculated.

While the IFAS is typically considered to be an expensive solution to wastewater treatment, the present work has identified candidate areas where economic gains may be made to improve its accessibility for developing countries. Although the earlier designs of the technology have favoured SS for its construction, this work has shown that adoption of alternative materials such as MS, GFRP, RCC and HDPE can yield substantial economic gains in the technology's early life stages. More significant is the possible savings that can be made by adopting alternative aeration strategies such as IA, providing associated challenges can be overcome. Under the optimal oxic/anoxic cycle, aeration cost savings of ~45% are found to be possible. Alternatively, by optimizing the DO setpoint in CA aeration energy costs can be reduced by ~12% while achieving improved effluent quality. Finally, the cost of maximized TN removal performance was investigated for the IFAS system which was found to incur between $15–18,000 throughout its service life depending on tank material.

Further work is now required to investigate the net value of incorporating a post-anoxic tank with supplementary mixing in the IFAS configuration to inform its value as a possible enhancement of this technology based on both economic and environmental considerations. Furthermore, while the present work has determined the economic profile of the alternative aeration strategies, further work should now look to integrate these results with other indicators such as environmental burden and technical performance. By doing so, the overall sustainability of these strategies can be better understood which in turn may benefit sustainable development in urban wastewater management.

## Credit author 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

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.deveng.2022.100103.

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