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Technology Selection for Wastewater Treatment in the Maldives

SUMA KHALID MOHAMED, HECTOR GARCIA HERNANDEZ, & CHRISTINE MARIA HOOIJMANS

IHE Delft Institute for Water Education, The Netherlands

ABSTRACT *In the Maldives, the discharge of untreated wastewater into the sea poses a significant threat to public health and the marine environment. This study proposes technically feasible, sustainable, and economical wastewater treatment technologies appropriate for small islands in the Maldives. Out of the 187 residential islands in the Maldives, three islands (HA. Dhidhdhoo, HA. Hoarafushi, and HA. Ihavandhoo) were selected as study areas. This study characterized the wastewater from these islands using physiochemical and microbiological water quality assessment parameters. The Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR), an open-source software developed by the Humbolt State University in 1993, was used to simulate the performance of different wastewater treatment processes to treat the characterized wastewater. The feasible alternatives identified from these simulations were analyzed using a Multi-Criteria Analysis (MCA), considering various indicators that influence the decision-making process. The wastewater quality assessment revealed that the wastewater generated in the three islands produced low concentrations of chemical and biological oxygen demand (COD and BOD), with concentrations ranging from 267 – 309 mg/L and 128 – 219 mg/L, respectively. Nitrate and phosphate concentrations were also low (5.7 – 18.0 mg/L and 2.8 – 14.9 mg/L, respectively), where these concentrations in Dhidhdhoo and Hoarafushi were already within the maximum allowable limits of 15 mg/L and 10 mg/L, respectively, for discharge into the deep sea. Based on the findings, secondary treatment technologies such as membrane bioreactors (MBR) and sequencing batch reactors (SBR) with Ultraviolet (UV) disinfection were found to be the most feasible options for treating the wastewater. These results were further checked for robustness using a sensitivity analysis. This study demonstrates that the proposed methodology is suitable for technology selection and can provide valuable information for policymakers and stakeholders in the country and serve as a basis for future studies.*

Keywords: Wastewater Characterization, Wastewater Treatment Trains, WAWTTAR, Multi-Criteria Analysis, Maldives

Introduction

Sanitation services that are both safe and hygienic are essential for the maintenance of healthy communities. In the 1970s, outbreaks of cholera and diarrhoea in the Maldives were associated with the contamination of groundwater from improperly managed on-site septic tanks and soak pits (Mohamed, 2020). This led to the replacement of the on-site systems with island-level piped networks for wastewater collection. To ensure access to safe water supply and adequate sewerage services as

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per the National Strategic Action Plan 2019-2023 (The Government of Maldives, 2019), the government is working towards establishing water and sewerage systems in all islands by the end of 2023.

Being surrounded by the sea, wastewater disposal over the reefs into the sea is the commonly applied solution to wastewater management in the Maldives (Ministry of Environment and Energy, 2017). The use of marine outfalls for wastewater disposal is grounded on the dilution and dispersion capacity of the sea by the sheer volume of water and strong currents, respectively (Elliott, 2003; Ludwig et al., 1988). For this reason, the disposal of wastewater through a marine outfall is often posed as an alternative for wastewater treatment (Roberts, 2016). However, various factors affect the effectiveness of the outfall in diluting and dispersing the effluent and safely disposing of wastewater. These include (i) the length of the outfall, which determines the distance from the land and coastal areas of recreational and environmental value, (ii) the location and depth of the outfall, which relates to the strength of tidal currents and extent of horizontal dispersion to carry away the effluent respectively, and (iii) the diffuser systems at the end of the outfall pipeline at the point of discharge which determines the initial dilution of the effluent (Ludwig et al., 1988; Mara, 2003; Roberts et al., 2010).

These factors are accounted for in Environmental Impact Assessments (EIA) (Saaneez, 2021; Sandcays, 2014; Shah, 2021) performed for the establishment of sewerage systems in the Maldives. These EIAs reported that the ends of the outfall pipelines are fitted with diffusers and are located at depths of around 5-10 m outside the reef edge, ensuring that the tidal currents dilute and disperse the wastewater. Moreover, the high salinity of seawater is deemed to inactivate the pathogenic microorganisms in the wastewater effluent. Since these islands are producing only domestic wastewater due to the absence of industries, marine pollution due to untreated wastewater disposal is assumed to be negligible (EPOCH Associates, 2020).

Despite these careful design considerations and assessments, there are growing concerns over the disposal of untreated wastewater into the sea. The raw wastewater effluents might contain high concentrations of organic matter, nutrients, suspended solids, and pathogens (Roth et al., 2016; Teodoro et al., 2010). These pollutants, directly and indirectly, affect human health and the environment, which include (i) eutrophication caused by high loads of nutrients, (ii) deterioration of water quality in the vicinity of the outfall caused by high loads of pathogenic microorganisms, (iii) decrease in the abundance and diversity of fish and benthos caused by the accumulation of chemicals and other toxic contaminants in these organisms and sediments, and (iv) spread of diseases and infections due to pathogenic microorganisms (Betancourt et al., 2014).

The impacts of untreated wastewater disposal can be detrimental to the small islands of the Maldives. Being surrounded by the sea, coral reefs are of great value for coastal protection and tourism in the Maldives. Increased risk of eutrophication due to high nutrient loads is unfavourable for healthy coral growth (Elliott, 2003; Water Solutions, 2017). Despite the detrimental effects of salinity and solar radiation in the marine environment on pathogenic microorganisms, E. coli has demonstrated an adaptive capacity, as evidenced by its ability to persist in these settings and sustain its disease-spreading potential upon exposure, as noted by (Jozi & Šoli, 2017). Moreover, there are increased risks of outfall pipe breaking due to the strong waves, causing untreated wastewater to leak into the coral reefs and lagoons and may cause harmful pollutants to sweep ashore (EPOCH Associates, 2020).

From 1998 onwards, all the Maldives tourist resorts must treat their wastewater before discharging it into the sea. The wastewater treatment plants (WWTP) are managed by the resort management and are not regulated and monitored by the Utility Regulatory Authority to date. Hence, information on the technologies and their efficiency in removing pollutants is limited.

There are 30 wastewater treatment systems established by external parties in the residential islands of the Maldives (JICA, 2022). These include, inter alia, constructed wetlands (reed beds) in L. Isdhoo, L. Kalaidhoo, and L. Dhanbidhoo by JICA in 2006, which are partially operational. However, there is a lack of maintenance being performed which caused poor drainage and uncontrolled vegetative growth (FENAKA Corporation, personal communication, September 13, 2022). Moreover, the establishment of these reed beds was expensive and required a large land area, which may not be well-suited for replication in other small islands (Sandcays, 2014).

The rotating biological contactor (RBC) system in Th. Vilufushi, which was established by the British Red Cross in 2008 (Sandcays, 2014), and extended aeration (EA) activated sludge systems in Sh. Funadhoo, B. Eydhafushi, and M. Muli, established by UNICEF under Tsunami Reconstruction Project in 2008, are non-operational as major repairs and expensive spares are needed, which are unavailable locally. Furthermore, due to the lack of technical expertise in operating and maintaining these outsourced foreign technologies, the wastewater treatment plants have been bypassed (FENAKA Corporation, personal communication, September 13, 2022).

Sewerage systems established under the OFID grant phase 1 include moving bed biofilm reactors (MBBR) in N. Velidhoo, R. Hulhudhufaaru, B. Thulhaadhoo, and GA. Kolamaafushi. These systems were commissioned in 2019 but were not tested with sludge and hence are non-operational. They also need minor mechanical repairs and training of technicians to begin operations. Some wastewater treatment plants are unable to operate due to the high energy requirement and the low voltage issues faced in the islands (FENAKA Corporation, personal communication, September 13, 2022). The extended aeration activated sludge systems in GDh. Thinadhoo and Gn. Fuvahmulah City are operational. However, in GDh Thinadhoo, the influent wastewater is bypassed during heavy rainfall due to overflow issues. The treated effluent quality is not monitored in any of the wastewater treatment plants (FENAKA Corporation, personal communication, September 13, 2022). Wastewater management presents a significant challenge in small developing nations, primarily attributable to a deficiency in technical proficiency, limited land and financial resources, and a mismatch between the technology employed and the available resources (Cossio et al., 2018). Hence, there is a strong incentive to explore wastewater treatment technologies that are appropriate for small developing islands in the Maldives.

The national wastewater quality guidelines of the Maldives (URA, 2022b) present the minimum treatment required for the wastewater generated in the residential islands before disposal into the sea. It states that solid removal is the minimum treatment required for populations less than 1000 people and wastewater flows less than 100 m3/day. For islands with populations greater than 1000 people and wastewater flows between 100 – 500 m3/day, the solids are required to be removed and biologically treated. Primary and secondary treatment is required for those islands with populations greater than 1000 people and where the wastewater flow exceeds 500 m3/day.

The government of Maldives has planned to establish environmentally friendly wastewater treatment options with low costs of operation, maintenance, and management in the residential islands (The Government of Maldives, 2019). However, these efforts are limited to a preliminary design of proposed technologies for wastewater treatment that will be built at a later phase of the project (The Government of Maldives, 2019). This exclusion of wastewater treatment in the initial design is justified based on the dilution and dispersion capacity of the sea, minimizing the harm raw wastewater may cause to the marine environment (Sandcays, 2014; Saaneez, 2021; Shah, 2021). Hence, in all these systems, untreated wastewater is discharged into the sea via marine outfall pipelines (JICA, 2022).

In the preliminary designs of wastewater treatment plants in the Maldives, Sequencing Batch Reactor (SBR) is mostly proposed as the secondary wastewater treatment technology as they are also widely utilized in the Maldivian tourist resorts and can therefore be easily replicated in other residential islands (Water Solutions, 2017; EPOCH Associates, 2020; Saaneez, 2021; Shah, 2021). However, there is no clear indication of how the wastewater treatment technologies established in the Maldives were selected, and there are no publicly available feasibility studies that provide insight into the selection process. This lack of information prompted this study to conduct a techno-economic assessment of various treatment options through a comprehensive wastewater characterization, process simulations, and a Multi-Criteria Analysis (MCA). The outcome of this study is to identify the most suitable and cost-effective technology that can be adopted for WWTPs in Maldives, which could lead to improved water quality and enhanced environmental sustainability.

Materials and Methods

Description of the Study Areas

The Maldives is in the Indian Ocean between 7° north to 0.5° south of the equator, southwest of India. It consists of 1192 islands spanning an area of 916,000 km2, with 99.6% of it being sea. The islands extend 870 km in length and 128 km in width, with a maximum natural elevation of approximately 2.4 meters from the main sea level (Stevens & Froman, 2019).

This study focuses on Dhidhdhoo, Hoarafushi, and Ihavandhoo, which are residential islands located in the Haa Alif Atoll of the Maldives (Figure 1). With a focus on islands with populations ranging from 1000 to 4999 individuals, a characteristic shared by approximately 70 out of the 187 residential islands in the Maldives, and most of the islands having small land areas of less than 1 km2, the findings of this investigation can be extrapolated to similar islands. Despite the presence of wastewater collection networks and marine outfalls in these islands, the absence of wastewater treatment plants necessitates a comprehensive evaluation of the current wastewater management practices. Additionally, for ease of wastewater sample transport to the water quality testing laboratories located in Male' city, the selection of three islands from the same atoll, including HA. Hoarafushi, which houses a Domestic Airport, is justified.

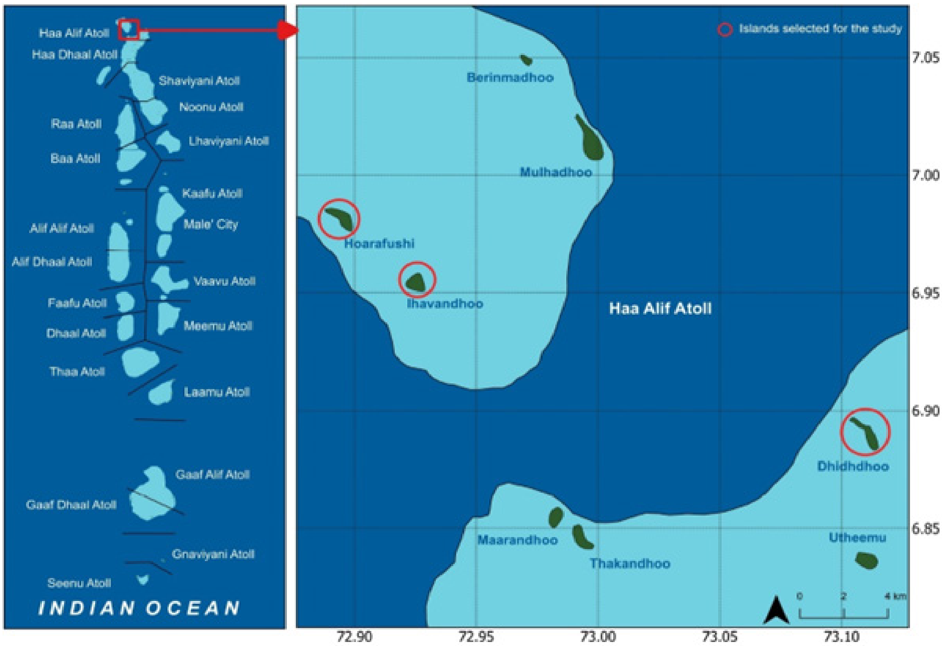

Figure 1: Location of the Maldives and the three islands selected as study areas. Source: Adapted from Humanitarian Data Exchange, (2021).

Collection of Wastewater Samples

For all three islands, 24-h composite samples of raw wastewater were collected from the final sewer pump station right before the marine outfalls. The samples were stored on ice at 4^0C in cool boxes and sent to water quality testing laboratories within 24 hours after sample collection. The physicochemical and microbiological parameters for the wastewater characterization were performed by the National Health Laboratory and Male' Water and Sewerage Company (MWSC) Laboratory by applying standard methods for the analysis of wastewater samples.

Simulation of Wastewater Treatment Technologies

A prefeasibility planning software named Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR), developed by the Humbolt State University in 1993 (Finney & Gearheart, 2004), was used to simulate the technical and economic performance of different technologies in treating the characterized wastewater. The design of the treatment trains was focused on secondary treatment technologies and disinfection processes in treating wastewater streams. The technologies selected for these treatment trains are presented in Figure 2.

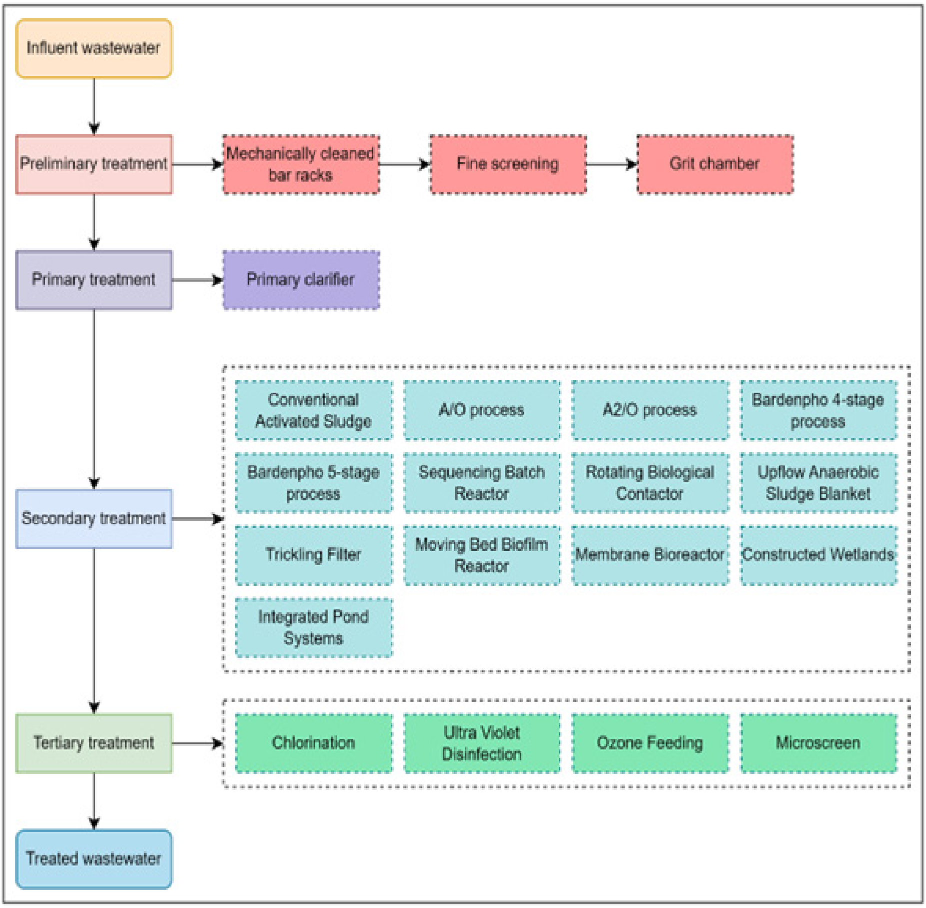

Figure 2: Wastewater treatment processes evaluated in this study.

The software requires the user to create community profiles by recording location-specific information. The simulations performed present the total capital and operational costs, land cost and area requirement, final effluent quality, and scores for adaptability to upgrade and to varying hydraulic loading and flows. The inputs and outputs of the software are summarized in Figure 3.

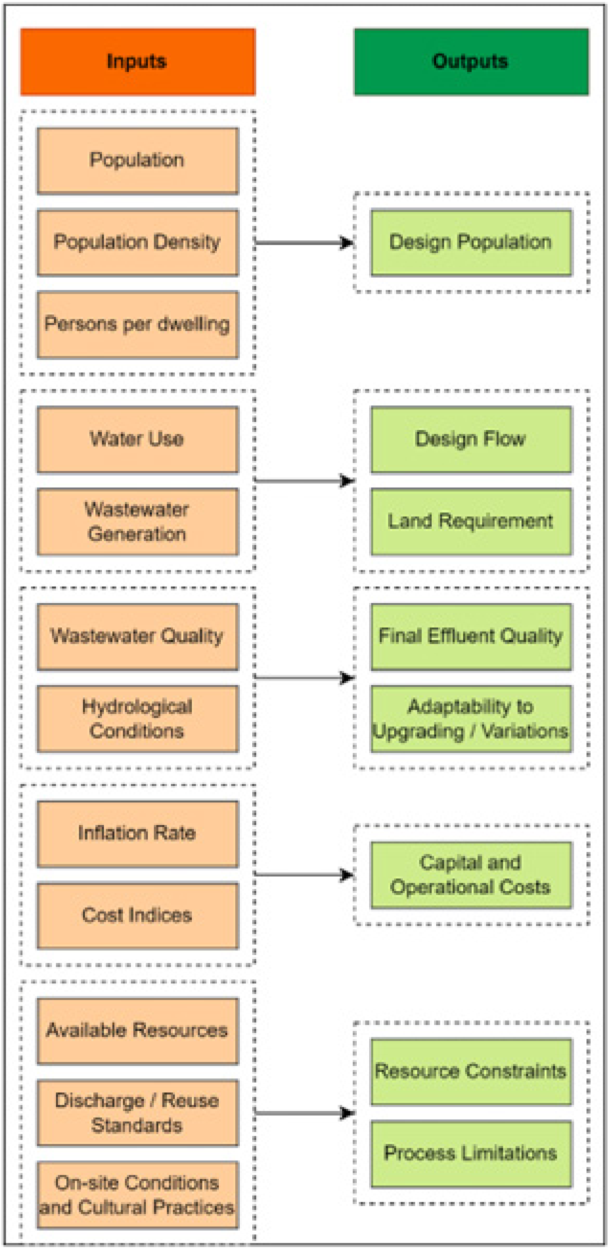

Figure 3: Inputs and outputs of the WAWTTAR software used for the process simulations.

To evaluate the feasibility of the treatment trains in meeting the water disposal guidelines, the national effluent quality standard for treated wastewater disposal into the sea set by the Utility Regulatory Authority (2022) was used as a standard in WAWTTAR. The removal of Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), nitrate, ammonia, phosphate, and faecal coliforms was tracked in the simulations because these are the major pollutants required to be treated and removed in the effluent quality guidelines. The starting year was 2022, and the planning horizon was 20 years, considering factors such as demographics and inflation rates.

Multi-Criteria Analysis (MCA)

The Weighted Sum Model (WSM) is an MCA tool that ranks the available options by setting specific criteria that are weighted based on relevance and priority. It is widely used for decision-making in water and sanitation projects (Garfi & Ferrer-Marti, 2011). In this study, to perform the MCA, four main aspects were considered: technical, environmental, economic, and social aspects. For each of these aspects, specific criteria and indicators were defined based on the commonly used selection criteria for sanitation projects. Using the WSM approach, the values obtained for the indicators were normalized from 0 to 1 using Microsoft Excel, 0 being least preferred and 1 being most preferred. For m alternative treatment trains and n indicators, the WSM score was calculated as follows.

$$A_i^{WSM} = \sum_{j=1}^{n} w_j v_{ij}, i = 1, 2, 3, .. m \qquad \text{(Equation 1)}$$

where w_j is the weight assigned to the indicator j and

v_{ij} is the value of alternative i for indicator j

(Triantaphyllou, 2000).

The MCAs of the feasible secondary wastewater treatment technologies and disinfection were scored out of 10 and 5 points, respectively. Current challenges for inadequate wastewater treatment are mainly due to a lack of funds for operations and maintenance of the existing systems. Hence, operational costs carried a higher weight compared to capital costs. The indicators for removal efficiencies had high priorities in this selection.

Moreover, the systems established in the Maldives by foreign agencies are often complex, and trained staff is limited on the islands for continuous operation. Hence, the complexity of the technology and skilled labour requirement is also addressed in this MCA. With limited information on wastewater generation and characterization in the islands, it is also important for the systems to be adaptable to upgrading and varying influent flows and qualities.

Environmental aspects mainly cover air and water pollution. This is indicated by the greenhouse gas (GHG) emissions and the concentrations of nutrients, pathogens, and toxic residuals in the final effluent.

For the continuous operation of wastewater treatment plants, public acceptance is vital. The most addressed public nuisances in wastewater treatment are odour, pests, noise, and aesthetics. The general criteria for technology selection adopted in this study are further explained in Supplementary Table 1.

A sensitivity analysis was performed for the MCA to observe the effects of changing the weightage assigned for each criterion and indicator. For the MCAs, four scenarios stated below were formulated, with priority given to different aspects in each scenario.

Scenario 1: All indicators were given equal weightage.

Scenario 2: The highest priority was given to the technical aspect, and the remaining indicators had equal weightage.

Scenario 3: The highest priority was given to the capital and operational costs of the economic aspect, and the remaining indicators had equal weightage.

Scenario 4: The highest priority was given to the environmental aspect, and the remaining indicators had equal weightage.

Results and Discussion

Characterization of Wastewater

On the day of the sample collection, no rainfall was recorded. The sunny weather with ambient temperatures between 27 – 31^{0}C during the day was associated with the high mean temperature (28^{0}C) of wastewater recorded onsite for the three islands. The pH was similar in the three islands, with values of between 7.1 – 7.2 (Table 1). This pH is suitable for the biological treatment of wastewater and reduces the need for pH-balancing processes in wastewater treatment trains.

The wastewater generated in Dhidhdhoo had the highest EC, salinity, TDS, and chlorides (3240 mg/L, 1.69%, 1621 mg/L, and 789 mg/L, respectively) among the studied areas (Table 1). This was associated with the salinized groundwater, which was mainly used for flushing toilets in the reclaimed area in the north and the residential areas near the coast. Wastewaters with salinity between 1 – 3.5% are considered high-salinity wastewaters (Zhao et al., 2020). Higher salinity reduces the biological activity of the microorganisms in wastewater treatment plants but are capable of treating wastewater with sodium chloride concentrations below 10 g/L (Linaric et al., 2013; Zhao et al., 2020). Hence, for wastewater treatment in Dhidhdhoo, no challenges are expected due to the high salinity of influent wastewater.

The BOD and COD in these islands were below 220 mg/L and 310 mg/L, respectively (Table 1). The BOD/COD ratios of raw wastewater in these islands corresponded to typical untreated municipal wastewater and were greater than 0.5, which showed easy treatment with biological processes (Metcalf & Eddy Inc et al., 2014). The concentrations of organic matter show that these islands produced low-strength wastewater (Mara, 2003; Metcalf & Eddy Inc et al., 2014).

The oil and grease content and total petroleum hydrocarbons (TPH) were low on all three islands. This may have been due to the samples being collected from below the floating scum in the pump station wells. Moreover, there are grease traps implemented in cafés and restaurants operating on these islands. This scum and grease are removed during the annual sewerage network maintenance works. Hence, this reduced the need for a grease removal unit in the wastewater treatment trains.

The nutrients in the wastewater were higher than the typical composition of municipal wastewater described by Metcalf & Eddy Inc et al. (2014), with nitrate and phosphate concentrations between 5.7 – 18.0 mg/L and 2.78 – 14.9 mg/L, respectively (Table 1). Total nitrogen was not measured in this study, and only inorganic nitrogen values were obtained. For the three islands, the nutrients were in similar concentrations to medium to high-strength wastewater (Henze & Comeau, 2008). For Hoarafushi, ammonium concentrations were 50 times higher (53.75 mg/L) than for the other two islands. The nutrient concentrations measured again from a new sample from Hoarafushi showed that the ammonium concentration remained high, and there was an increase in phosphate concentration as well. Hence, this indicates that the disposal of this wastewater without any treatment might pose higher environmental impacts such as eutrophication, and the treatment options need to have nutrient removal processes as well. In this study, the cause of a high ammonium concentration in Hoarafushi was not identified, and more research may be needed to fully understand the factors contributing to this parameter.

The microbiological tests were performed using Quanti-Tray®2000, which has a counting range of 1 – 2419 without any dilutions. At dilutions of 103, the bacterial counts exceeded the range. When a wastewater sample from Hoarafushi was tested again with a dilution of 105, the fecal coliform was quantified at 2.91×107 CFU/100 mL. Hence, in this study, coliform concentration was assumed to be 2.91×107 CFU/100 mL for all three islands. This also reflects the typical average faecal coliform concentration of 1×107 CFU/100 mL in untreated low-strength wastewater (Metcalf & Eddy Inc et al., 2014).

Table 1

Results of the water quality assessment performed for the raw wastewater generated in Dhidhdhoo, Hoarafushi, and Ihavandhoo, and the effluent quality standards for disposal of wastewater into the deep sea.

Parameter	Dhidhdhoo	Hoarafushi	Ihavandhoo	Effluent Standard
pH	7.2	7.2	7.1	5.0 – 9.5
Temperature (°C)	28.5	27.5	28.5	
Electrical Conductivity (μS/cm)	3240	1506	1262	
Salinity (%)	1.69	0.76	0.63	
Chemical Oxygen Demand (mg/L)	267	283	309	< 50
Biological Oxygen Demand5 (mg/L)	128	204	219	< 40
Total Dissolved Solids (mg/L)	1621	753	631	
Total Suspended Solids (mg/L)	176	194	279	< 150
Total Organic Carbon (mg/L)	41	70	95	
Oil and grease (mg/L)	1.7	14.9	0.4	< 5
Turbidity (NTU)	46.4	62.4	114	
Iron (mg/L)	<0.02	0.07	0.15	
Phosphate (mg/L)	9.10	2.78 / 13.20	14.9	< 10
Sulphate (mg/L)	155	<10	25	
Chloride (mg/L)	789	188	117	
Nitrate (mg/L)	10.9	5.7 / 7.9	18.0	< 15
Nitrite (mg/L)	0.055	0.121 / 0.290	0.083	
Nitrogen Ammonia (mg/L)	0.62	53.75 / 48.50	1.40	
Total Alkalinity (mg/L)	256	335	402	
Total Petroleum Hydrocarbons (mg/L)	0.32	0.071	0.14	
Total coliforms (CFU/100 mL)	$>2.42\times10^6$	$>2.42\times10^6$	$>2.42\times10^6$	
Fecal coliforms (CFU/100 mL)	$>2.42\times10^6$	$>2.42\times10^6$ / 2.91×10^7	$>2.42\times10^6$	< 100
Escherichia coli (CFU/100 mL)	$>2.42\times10^6$	$>2.42\times10^6$	$>2.42\times10^6$	< 1

Assessment of Wastewater Treatment Technologies

Detailed results of the simulations run on WAWTTAR are presented in Supplementary Table 2 - 5.

The treatment of the characterized wastewater modeled using the WAWTTAR software indicated the need for secondary wastewater treatment because when the treatment was limited to only preliminary and primary treatment levels, the BOD, nutrients, and coliform counts were not in compliance with the effluent quality standards.

Dhidhdhoo and Hoarafushi had a similar wastewater characterization, with nutrient concentrations below the effluent quality standards. Hence, more treatment trains than for Ihavandhoo, even with limited nutrient removal processes such as conventional activated sludge (CAS), RBC, Upflow Anaerobic Sludge Blanket (UASB), Trickling Filters, aerobic Membrane Bioreactors (MBR) and MBBR, were feasible for these two islands. Among the chosen treatment trains, the UASB was the only secondary wastewater treatment technology that was unable to reduce the BOD to the maximum allowable limit of 40 mg/L. Pairing UASB with a Trickling Filter and integrated pond system (IPS) improved BOD removal, highlighting the need for post-treatment aerobic processes in the case of anaerobic technologies.

While UASBs are known for their cost-effectiveness, primarily attributed to their potential for biogas production and low sludge production rate, approximately 5 times less than conventional activated sludge systems, their applicability is hindered in small islands of the Maldives. This limitation arises from the low organic content, expressed in terms of COD and BOD, present in the characterized wastewater. The low organic content restricts the biogas production capacity of UASBs to sufficient levels. UASB requires more land area to allow for the proper flow and treatment of the wastewater because a large volume of as much as 70% of the UASB reactor is occupied by the sludge blanket (Metcalf & Eddy Inc et al., 2014). Consequently, the feasibility of implementing UASBs in these small islands is compromised, primarily due to insufficient BOD removal, low pathogen removal efficiency, and limited adaptability to handle varying flows.

The application of constructed wetlands (CW) and IPS in the context of the small islands in the Maldives presents certain challenges and considerations. Dhidhdhoo exhibits feasibility for CW implementation due to its manageable influent BOD levels, unlike Hoarafushi and Ihavandhoo, with influent BOD concentrations exceeding 200 mg/L. CW is known for its low operational and capital costs and is relatively simple to operate, making it an attractive option. Similarly, IPS demonstrates promising pollutant removal capabilities. According to Mara (2003), technologies such as CW and IPS are well-suited for developing countries with tropical climates because these natural systems are easy to operate at a low cost. However, one crucial drawback is their land-intensive nature, requiring a significant area for effective implementation. This limitation is further emphasized when considering the small land sizes characteristic of the islands of the Maldives.

The sequencing batch reactor (SBR) emerges as a highly suitable technology for wastewater treatment in the Maldives. Among aerobic secondary treatment options, the SBR stands out due to its favorable characteristics, including the lowest capital cost, minimal sludge production, small footprint, and efficient nutrient removal. These factors render it a feasible choice for implementation on all three islands under consideration. The low capital cost and small footprint of SBR are attributed to its unique operation, where a single reactor performs a sequence of treatment steps in batches, eliminating the need for primary and secondary clarifiers (Mahvi, 2008; Dutta & Sarkar, 2015). Furthermore, the SBR's low sludge production rates are achieved through extended sludge retention times of 20 to 40 days, coupled with the recycling of sludge during subsequent reaction cycles (Metcalf & Eddy Inc et al., 2014). While an economic assessment conducted by Molinos-Senante et al. (2012) revealed comparable cost ranges for SBR, MBR, MBBR, Trickling Filters, and RBC, it was found that SBR had the highest capital cost among these technologies. This higher capital cost can be attributed to the need for more complex control systems and automatic instrumentation compared to conventional activated sludge processes. Additionally, SBR's operational costs were relatively higher when compared to constructed wetlands, IPS, and Trickling Filters, primarily due to the sophisticated automation of cycles and increased system maintenance requirements (Mahvi, 2008). Therefore, the application of SBR in the Maldives warrants careful consideration of the availability of skilled personnel and the financial resources necessary for its implementation.

The membrane bioreactor holds significant potential for wastewater treatment in the Maldives. Among the analyzed treatment trains, MBR demonstrated exceptional removal rates for BOD and TSS, achieving an impressive 98.4% and 99.6% removal, respectively. Furthermore, MBR exhibited the lowest land requirement due to the compact arrangement of membrane modules for efficient solid-liquid separation and the maintenance of a high Mixed Liquor Suspended Solids (MLSS) concentration. This allows for the design of smaller tanks, optimizing space utilization.

Notably, MBR was the only technology capable of reducing faecal coliform levels below 100 CFU/100 mL due to the size exclusion properties of its membranes. However, it is important to acknowledge that tertiary treatment and disinfection are necessary for other secondary technologies. Despite these advantages, MBR does present challenges, including fouling issues and the need for high maintenance and technical expertise. It is worth mentioning that the Maldives already utilizes reverse osmosis (RO) membrane technology in its water systems, indicating potential familiarity with such advanced technologies in the future. MBR represents a viable option for achieving clean water for reuse, although currently, wastewater reuse practices are not implemented in the Maldives.

The application of nutrient removal processes in wastewater treatment is crucial in the Maldives, considering the nutrient concentrations in the characterized wastewater. Nitrate and phosphate concentrations varied across the studied islands. While nitrate levels in Dhidhdhoo and Hoarafushi were 10.9 mg/L and 5.7 – 7.9 mg/L, within the maximum allowable limits of 15 mg/L for nitrate and 10 mg/L for phosphate, this was not always the case for phosphate. The phosphate concentrations in Hoarafushi were 2.78 and 13.20 mg/L in two different samples, exhibiting that the concentration may occasionally exceed the permissible limit of 10 mg/L. In Ihavandhoo, both nitrate and phosphate concentrations were higher than the permissible limits. Thus, it is evident that addressing nutrient removal is crucial to ensure compliance with effluent quality standards and prevent nutrient loading into the environmentally sensitive marine environment of the Maldives.

The feasibility of disinfection processes was compared by adding liquid chlorination, ultraviolet (UV) disinfection, and ozone feed as a tertiary treatment. The results showed that UV disinfection had a higher treatment efficiency compared to liquid chlorination and ozone feeding. Among the three disinfection processes, only UV disinfection produced effluents with coliform counts (79 CFU/100 mL) lower than the maximum allowable concentration of 100 CFU/100 mL. Similar results were obtained by Liberti & Notarnicola (1999), where UV was the only treatment capable of complying with the Italian standard of 2 CFU/100 mL compared to ozone and peracetic acid (PAA). However, doubling the chlorination dose and using a combination of chlorination with ozone reduced the faecal coliforms to 2 CFU/100 mL, which also complies with the effluent quality standards.

The results also showed that UV had the lowest cost among the disinfection processes. According to Tak & Kumar (2017), UV has a high initial cost but has 63% lower operational and maintenance costs compared to chlorination, making it a cost-effective alternative. Moreover, UV systems require the least space, while ozone feed requires the most space. The land area required for chlorination and UV disinfection was similar for the three islands. However, greater fluctuations were observed for ozone feed with changes in wastewater flow rates.

In Ihavandhoo, where the influent TSS was higher than that in Dhidhdhoo and Hoarafushi, the simulations showed that when TSS exceeds 15 mg/L before disinfection, UV disinfection is infeasible. Hence, adding a tertiary treatment, such as a microscreen before disinfection, reduced the TSS to make UV feasible with minimal additional cost.

MCA for Feasible Wastewater Treatment Technologies

Out of the 11 feasible secondary wastewater treatment technologies for both Dhidhdhoo and Hoarafushi (Figure 4A), MBR had the highest WSM score of 6.85 and 6.79 out of 10, followed by SBR with scores of 5.90 and 5.82, and CAS with scores of 5.89 and 5.90 respectively.

Despite getting lower scores for the economic aspects, such as capital and operational costs, the high scores for MBR were accounted for by the technical aspects. This includes high effluent quality in terms of BOD, TSS and faecal coliforms, low sludge production, and the high adaptability to upgrading, varying hydraulic loading, and varying influent quality, which was assigned high weights due to their importance in the selection of wastewater treatment technologies.

For Ihavandhoo, out of the three feasible solutions, SBR obtained the highest score of 6.23 out of 10, followed by A2/O and Bardenpho 5-stage process, with scores of 3.85 and 3.03, respectively. Despite having the highest adaptability scores, SBR had lower scores for the technical aspects due to lower BOD and TSS removal rates compared to A2/O and Bardenpho 5-stage process. However, SBR had high scores for environmental and economic aspects due to its better performance at removing nutrients, low capital, and operational costs, and low land requirement, which were also equally important indicators in this MCA. The modified activated sludge processes, such as A2/O and Bardenpho 5-stage process, had the lowest score due to their high costs, high sludge production, and high land requirement.

MBR got very high scores in Dhidhdhoo and Hoarafushi but was infeasible for Ihavandhoo due to the absence of nutrient removal processes in the treatment train. A2/O being one of the feasible solutions for Ihavandhoo, where nutrient removal was necessary to comply with the effluent quality standards, and MBR being compatible with modifications, it is also proposed that the MBR design used in WAWTTAR is modified with different zones with and without oxygen. Modified A2/O-MBRs are being explored to improve the nutrient removal of MBRs (Wang et al., 2019; Xue, 2022).

SBR and MBR have been ranked high in previously conducted studies. In studies utilizing different MCA tools to assess wastewater treatment plant designs for small communities (Molinos-Senante et al., 2012; Molinos-Senante et al., 2014; Molinos-Senante et al., 2015), MBR and SBR were identified as the most feasible technologies among constructed wetlands, IPS, MBBR, RBC, Trickling Filters, and extended aeration.

Among the different disinfection processes evaluated in this study, doubling the chlorination dosages was the most feasible solution with scores of 3.05, 3.04, and 3.20 out of 5.0 points for Dhidhdhoo, Hoarafushi, and Ihavandhoo respectively (Figure 4B). UV disinfection came in second with a difference of a mere 0.1 – 0.2 points for Dhidhdhoo and Hoarafushi and a lower score for Ihavandhoo (score of 3.01) due to the additional costs incurred by adding a microscreen. The high costs and land requirements associated with ozone feeds reflected the lowest score for the combined process of chlorination and ozone.

The high scores for doubling the chlorination were associated with lower faecal coliform concentration after disinfection. However, UV had better scores for environmental and economic aspects which were also important indicators of the study, giving these two treatment trains similar scores. Chlorination had lower scores for environmental aspects because it produces toxic by-products, unlike UV disinfection (Liberti & Notarnicola, 1999). Increasing the dosage of chlorine to meet the effluent quality further exacerbates the negative impacts of chlorination on the environment. A sustainability assessment performed by Liberti & Notarnicola (1999) to evaluate alternative disinfection processes for chlorination showed that UV disinfection is one of the most feasible solutions to reduce the discharge of pathogens into the environment. Hence, having similar scores, UV is preferred over chlorination at higher dosages. In the Maldives, where the islands are dispersed, it is also important to consider the risks associated with the transport of chemicals such as chlorine. In this sense, UV disinfection is more favourable as it has no toxic residuals that may be released into the marine environment and less operational requirements and chemicals.

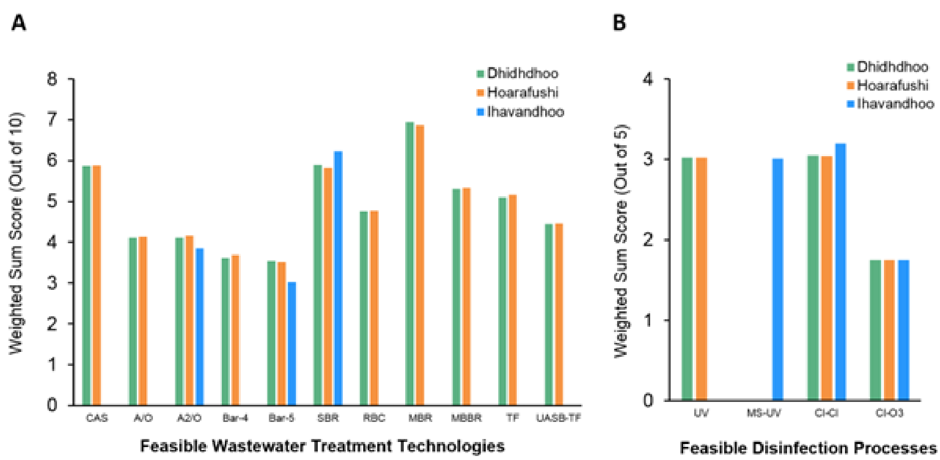

Figure 4: Weighted sum scores from the assessment of feasible secondary wastewater treatment technologies (A) and disinfection processes (B).
Note: *CAS – Conventional Activated Sludge; A/O – Anaerobic/Oxic; A2/O – Anaerobic, Anoxic/Oxic; Bar-4 – Bardenpho 4 stage; Bar-5 – Bardenpho 5-stage; SBR – Sequencing Batch Reactor; MBR – Membrane Bioreactor; MBBR – Moving Bed Biofilm Reactor; TF – Trickling Filter; UASB-TF – Upflow Anaerobic Sludge Blanket with Trickling Filter; UV – Ultraviolet Disinfection; MS-UV – Microscreen followed by UV Disinfection; Cl-Cl – Chlorination (2 steps); Cl-O3 – Chlorination followed by ozone feeding.*

Sensitivity Analysis

The sensitivity analysis for the MCAs performed for the feasible secondary wastewater treatment technologies (Table 2) showed that changing the weights assigned to the indicators had minor effects on the ranking of the alternatives, with MBR and SBR still obtaining the highest weighted sum scores. When all indicators were given equal weights and when technical indicators were prioritized (scenarios 1 and 2), MBR obtained the highest scores, whereas SBR obtained the highest scores when economic and environmental indicators were prioritized (scenarios 3 and 4). For Ihavandhoo, for all scenarios, SBR had the highest score depicting its appropriateness in all aspects compared to modified CAS systems such as A2/O and Bar-5.

The sensitivity analysis for the MCAs performed for the feasible disinfection processes (Table 2) showed that for all scenarios except scenario 2, where the technical indicators were prioritized, UV disinfection obtained the highest scores. In scenario 2, chlorination at higher dosages obtained the highest score but obtained much lower scores when economic and environmental indicators were prioritized. This showed that UV disinfection has an overall better performance.

Table 2
Sensitivity analysis of the MCA performed for the feasible technologies.

Prioritized Aspect	Scenario 1 Equal	Scenario 2 Technical	Scenario 3 Economic	Scenario 4 Environmental
Secondary Wastewater Treatment Technology				
Dhidhdhoo	MBR	MBR	SBR	SBR
Hoarafushi	MBR	MBR	SBR	SBR
Ihavandhoo	SBR	SBR	SBR	SBR
Disinfection				
Dhidhdhoo	UV	Cl-Cl	UV	UV
Hoarafushi	UV	Cl-Cl	UV	UV
Ihavandhoo	MS-UV	Cl-Cl	MS-UV	MS-UV

Note: SBR – Sequencing Batch Reactor; MBR – Membrane Bioreactor; UV – Ultraviolet Disinfection; MS-UV – Microscreen followed by UV Disinfection; Cl-Cl – Chlorination (2 steps).

Implications and Recommendations for Wastewater Treatment in the Maldives

The implementation of a centralized sewerage network in every inhabited island in the Maldives represents a significant investment. In a developing country like the Maldives, where financial resources are limited, and there is a great dependence on external investors the high costs associated with wastewater treatment can pose a significant challenge in terms of prioritization (Massoud et al., 2009). To avoid investing in technologies that may not be appropriate for local conditions and subsequently attributing any shortcomings to the lack of technical or financial capabilities within the country, it is crucial to adopt a long-term planning approach that focuses on sustainable water management (Massoud et al., 2009).

This study presents a methodology useful for supporting decision-makers in wastewater management. The assessment of wastewater treatment technologies, which includes performance simulation using WAWTTAR and Multi-Criteria

Analysis (MCA), examined various wastewater treatment technologies capable of treating the wastewater to the national effluent quality standard, suitable for small islands in the Maldives.

It is important to note that wastewater treatment is not only financially demanding but also labor-intensive. Therefore, selecting the most technically capable technology may not always be the most practical option. Despite the acknowledgment of dilution and dispersion in the deep sea according to EIAs and national wastewater quality guidelines, the existing effluent quality guidelines do not account for dilution factors when setting the maximum allowable limits for discharge.

For example, the national effluent quality guideline stipulates that wastewater should be treated to COD and BOD levels below 50 mg/L and 40 mg/L, respectively. However, in Sri Lanka, the discharge of wastewater into marine waters requires a dilution factor of 8. As a result, the effluent COD and BOD limits are set as high as 250 mg/L and 100 mg/L, respectively (Board of Investment of Sri Lanka, 2011).

The wastewater analyzed in this study exhibits similar COD and BOD values to the effluent wastewater in Sri Lanka, suggesting that advanced treatment of wastewater may not be necessary for the small islands of the Maldives when discharging into the deep sea. Therefore, it is recommended that the effluent quality guidelines be revised to establish more practical limits that consider the end use or disposal environment. For instance, these stringent effluent guidelines may be maintained if there are plans to implement more reuse purposes, such as utilizing treated wastewater for irrigation or landscaping.

Moreover, it is crucial to prioritize technologies that offer the best balance of technical capabilities, operational efficiency, ease of management, and environmental impacts and those that can be successfully replicated in similar local conditions, thereby ensuring effective and efficient wastewater treatment without imposing an excessive financial burden.

Based on the results of this study, the following treatment trains for wastewater treatment are proposed for the small islands of the Maldives to treat the wastewater to the national effluent quality standard.

- Preliminary treatment - sequencing batch reactor - UV disinfection (with a microscreen if necessary), or
- Preliminary treatment - primary clarifier - membrane bioreactor (modified with nutrient removal processes) – UV disinfection.

In addition to their excellent technical performance, these technologies also require less land area and produce less sludge, making them particularly well-suited for islands with limited land availability and resources.

However, it is important to acknowledge that wastewater treatment is a relatively new operation in the Maldives that has not yet been effectively established, and hence, wastewater treatment in the Maldives faces additional challenges.

Informed decision-making and policy changes must consider several potential obstacles, including limited technical expertise, scarcity of local resources, challenges in procuring spares from abroad, and high operational costs, all of which pose significant challenges. Especially on remote islands where technical expertise is low, regardless of the technology selected, it is crucial to building technical capabilities and train operators to ensure the continuous operation of the wastewater treatment plant.

Limitations

WAWTTAR, an open-source software tool, provides flexibility for updating the process data with recent findings of their performance. It enabled the creation of new processes, such as MBR and MBBR, in this study. However, as WAWTTAR was developed in 1993, the absolute costs presented in this study are based on 1992 values and are not recommended to be used for cost analysis. Instead, they serve as estimations for cost comparison and preliminary assessment of wastewater treatment in the Maldives.

Moreover, costs of wastewater treatment vary greatly from place to place depending on several factors, such as the quality of influent wastewater and the level of treatment required to comply with the effluent quality standards, and the availability of resources to establish the selected wastewater treatment technology (Qadir et al., 2010). Hence, further research is needed to investigate the technical and economic aspects of the selected technologies in the context of the Maldives. The study can also be further improved with the involvement of different stakeholders, decision-makers, and expert opinions to address the multiple dimensions of technological selection.

Conclusions

This study aimed to identify the most feasible technologies for wastewater treatment in the small islands of the Maldives to meet the effluent quality standards for the safe discharge of wastewater into the deep sea. To achieve this objective, a methodology that involved the use of wastewater characterization and technology selection via performance simulations using WAWTTAR and further analysis with an MCA approach was utilized.

The wastewater quality assessment showed low concentrations of organic matter and nutrients, characterizing the wastewater as having low strength. Assessing various wastewater treatment technologies using the WAWTTAR software and the MCA approach, it was determined that secondary treatment was necessary to meet effluent quality standards. Different treatment trains were feasible for Dhidhdhoo and Hoarafushi, but additional nutrient removal processes were required. Among the technologies analyzed, the sequencing batch reactor (SBR) emerged as a highly suitable option for all three islands, offering low capital costs, minimal sludge production, a small footprint, and efficient nutrient removal. The membrane bioreactor (MBR) showed excellent removal rates for BOD and TSS, as well as the ability to reduce faecal coliform levels below permissible limits. However, it presented challenges such as fouling issues and higher maintenance requirements. Moreover, anaerobic technologies such as the UASB and land-intensive technologies such as constructed wetlands and pond systems were found to be the least feasible for small islands of the Maldives. UV disinfection was identified as the best disinfection process due to its high performance and lower negative environmental impacts compared to chlorination and ozone feeding.

Overall, this study provides valuable insights into the most feasible wastewater treatment technologies for the Maldives, which can be useful for policymakers and stakeholders in the country to ensure the protection of its natural resources and enhance its reputation as a sustainable tourist destination. The findings of this study can serve as a basis for future studies that aim to improve wastewater treatment on small islands. However, further research is needed to investigate the operational performance and sustainability of these technologies in the context of the Maldives to ensure practical solutions are being implemented.

Conflict of Interest

I hereby declare that I have no conflict of interest related to this research.

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