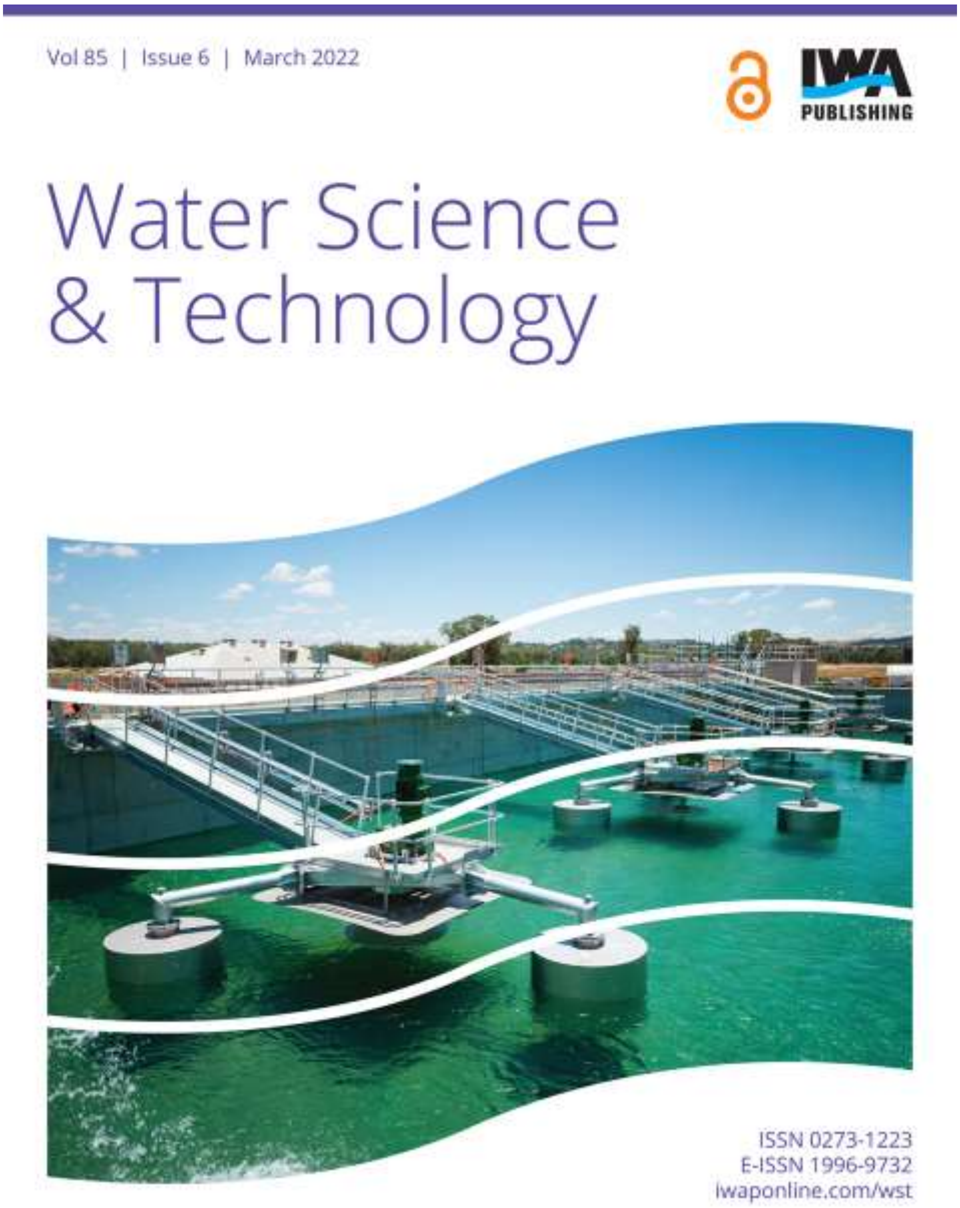

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Energy and reliability analysis of wastewater treatment plants in small communities in Ontario

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ABSTRACT

This paper presents energy and reliability analyses of eight wastewater treatment plants (WWTPs) operating in small communities in Ontario, Canada, with rated capacities ranging from 60 to 4,400 m^3/d. Five different treatment technologies were investigated, namely, rotating biological contactor (RBC), sequencing batch reactor (SBR), membrane bioreactor (MBR), lagoon, and extended aeration activated sludge process (EAAS). Energy benchmarking based on key performance indicators (KPIs) was used to quantify the specific consumption of energy in WWTPs per unit of the pollutant removed. The overall annual electrical energy consumption was correlated to the volume of treated wastewater, the population equivalent, and the amounts of TSS and BOD removed. The RBC plants showed a distinctive advantage for all energy KPIs assessed, while SBR plants yielded the highest values of energy KPIs. Analyses of the expected percentage of compliance with discharge standards and the coefficient of reliability (*COR*) based on the WWTPs' performance records showed that few WWTPs were able to achieve reliability levels over 95%, considering the mandated discharge standards under the current operating and maintenance conditions. Within each technology, the treatment train, operating conditions, maintenance level, and age of infrastructure were important elements that contributed to the large variability observed.

Key words: effluent quality standards, electrical energy consumption, energy intensity, energy key performance indicators, reliability analysis, wastewater treatment

HIGHLIGHTS

- Small WWTPs show limited data and often perceived of low environmental impact.
- KPIs provide a helpful tool to assess WWTPs' energy use.
- Lagoons followed by RBCs had the lowest consumption as per energy KPIs.
- Operation and maintenance impact reliability levels for BOD, TAN, and TSS removals.
- Reliability concept is useful in evaluating WWTP performance and setting standards.

GRAPHICAL ABSTRACT

INTRODUCTION

Rapid population growth and urbanization have led to increased wastewater generation and escalation in energy consumption in the wastewater treatment sector due to the increasingly stringent effluent quality standards (Di Fraia *et al.* 2018). Energy consumption and the inability to meet the stipulated effluent quality limits remain the main challenges facing wastewater treatment plants (WWTPs). Yet most WWTPs focus in their design on meeting effluent quality standards without consideration of energy requirements (Sparn & Hunsberger 2015; Neczaj & Grosser 2018). It was reported that treating wastewater to make it safe to return it to the environment consumes 2–4% of the total electricity used in the United States (Sparn & Hunsberger 2015; Copeland & Carter 2017). The electrical energy required for wastewater treatment varies widely with plant size, influent and effluent characteristics, pumping requirements, energy requirements for odour control, and the type of treatment processes and technologies used, but typically between 950 MJ/10^3 m^3 and 2,900 MJ/10^3 m^3 (between 0.26 and 0.81 kWh/m^3) (Metcalf & Eddy 2014). Several studies in the USA showed that municipal wastewater treatment plants are estimated to consume more than 30 terawatt-hours per year of electricity, equivalent to around $2 billion in annual electric costs (Lemar & De Fontaine 2017). It was indicated that 25–40% of WWTP operating costs in the USA were spent on electrical energy, 26% in Spain, and 25% in Portugal (Silva & Rosa 2015). In the 2016/2017 Annual Energy Conservation Progress Report released by the Environmental Commissioner of Ontario (ECO) in Canada, it was reported that municipal water and wastewater systems in Ontario used about 1,800 gigawatt-hours (GWh) of electricity and 40 million m^3 of natural gas in 2011, which is equivalent to 38% of the municipal energy consumption and accounted for 32% of reported municipal greenhouse gas (GHG) emissions with almost half of that coming from wastewater treatment (Saxe 2017).

Electric energy prices are likely to influence WWTP energy consumption among the various countries, where higher prices could provide stronger incentives for energy efficiency measures. For example, electricity in France is especially less expensive for industry (0.079 €/kWh) instead of 0.120 €/kWh in Spain, 0.130 €/k h in Germany, and 0.178 €/kWh in Italy (Longo *et al.* 2016). According to the ECO, water and wastewater systems cost Ontario about $260 million and these costs are expected to rise due to the increase in energy prices, population growth, ageing infrastructure, and increasingly stringent regulatory standards, which require more energy-intensive treatments. Thus, energy efficiency and treatment performance have been attracting attention from both environmental and economic perspectives (Saxe 2017).

Wastewater treatment is designed to make the treated water eco-friendly, but wastewater treatment facilities also leave an environmental footprint when they treat wastewater, for instance the organic matter and nutrients (N and P) removed from wastewater need to go somewhere, preferably recovered as resources. Moreover, the presence of such materials in the treated effluent should not exceed the prescribed effluent quality limits (Ward 2019).

Globally, research has mainly focused on large-scale systems where there is a wealth of operational and energy data available. In contrast, smaller WWTPs are typically disregarded mainly due to the lack of data or because they are perceived as having a low environmental impact. In fact, most small WWTPs have limited historical performance data due to the absence of rigorous routine monitoring mandates or exemption from regulatory requirements, which makes it challenging to predict performance or determine the impact (Bruce & Graham 2019). Generally, energy use per volume tends to be lower at larger treatment plants (Metcalf & Eddy 2014). It has been indicated that the economies of scale play a major role in energy conservation, where large WWTPs with treatment capacity over 10 MGD (37,850 m^3/d) have the greatest potential to recover energy, while small-size WWTPs serving populations of 10,000 or less have limited opportunities due to limited availability of funding and lack of expertise to conduct energy assessments on the facility level (Hanna *et al.* 2018). For example, despite encouraging the implementation of performance measures for energy efficiency, the Ontario Clean Water Agency (OCWA) indicated that energy assessment is included in their projects plans as a qualitative exercise mainly due to the lack of field data, especially in smaller municipalities. Further, it was highlighted that the alarming figures of energy consumption in the water and wastewater treatment sector still underestimate the actual energy figures due to the lack of monitoring and tracking of energy consumption (Saxe 2017). It has been estimated that activated sludge processes require more energy (0.33–0.6 kWh/m^3) than other treatments such as tricking filters (0.18–0.42 kWh/m^3) and lagoons (0.09–0.29 kWh/m^3), with an increase in energy requirements as the treatment process becomes more sophisticated and aeration becomes more intensive, reaching 2 kWh/m^3 (advanced wastewater treatment and/or water reuse and recycle) (Gude 2015; Guven *et al.* 2019).

There has been a lack of quantitative studies to support the energy consumption in the municipal wastewater sector in Ontario. All studies have combined water and wastewater treatment sectors, making it difficult to establish a baseline for benchmarking and comparing against different systems and regions, whether nationally or globally. Specifically, the treatment performance and energy consumption of small WWTPs are not well studied, despite the fact they play a vital role in the quality of water resources in rural and remote catchments. Thus, it is imperative to understand and benchmark energy consumption and treatment performance in small WWTPs in Ontario to determine a facility's baseline energy usage and treatment efficiency, identify potential energy-saving opportunities and generate information that can be used by operators of WWTPs, designers, managers, and policymakers in both evaluating and predicting the process performance and in addressing energy and water conservation. According to OCWA, a growing number of municipalities are participating in a comprehensive pilot program that identifies opportunities for energy saving and provides internal benchmarking data with over 150 water and wastewater facilities already maintained (OCWA 2017).

Reliability analysis provides essential information that can be used by the designers and operators of the WWTPs to evaluate treatment performance with respect to effluent quality parameters and regulatory requirements. Further, reliability analysis generates enough information to predict the treatment performance, based on the current operating conditions, which could help designers and policymakers set reasonable and practical discharge limits and avoid setting unrealistic parameter values (Oliveira & Von Sperling 2008).

Two essential aspects should be considered when assessing the reliability of a WWTP: (1) The probability that the WWTP is operating 'properly' and (2) the probability that the effluent meets or exceeds given criteria (Eisenberg *et al.* 2001). This paper presents an analysis of recent data from eight WWTPs in small communities in Ontario employing different biological wastewater treatment systems. The analyses included energy consumption, treatment plant performance, and performance reliability.

This study was conducted to: (1) provide and test new analytical approaches using the available historical data to assess the performance and improve the management of existing small WWTPs, and (2) assess and compare energy costs, treatment performance, and reliability level. A simple method for assessing the energy performance of wastewater treatment plants through combining energy performance indicators with a performance factor or a loading on the plant was proposed. To determine performance reliability, a probabilistic method based on the historical data was used to assess the percentage of compliance of a WWTP in meeting the treatment target or specified discharge standards. This approach can also help set realistic and practical discharge standards from an operational point of view (using historical operational records/data).

The proposed methods have been used to analyze some WWTPs in small communities in Ontario. The selected plants represent different treatment technologies, design, and management conditions as follows: (1) Rotating biological contactor (RBC) – three WWTPs, labelled here as: RBC-1 Facility, RBC-2 Facility, and RBC-3 Facility; activated sludge sequential batch reactor (SBR) – two WWTPs, labelled: SBR-1 Facility and SBR-2 Facility; Membrane bioreactor (MBR) – one plant, named MBR Facility; wastewater treatment lagoon – one plant, named: Lagoon Facility. The Lagoon Facility was later upgraded to a moving bed bioreactor (MBBR) plant; and extended aeration activated sludge process (EAAS)–one plant.

METHODS

Plants description and treatment processes

A total of eight WWTPs were used as case studies in this analysis. The processes description of each plant and the treatment steps were derived from its ECA and annual reports and are detailed as follows:

RBC-1 Facility

The RBC-1 Facility is located in Central Ontario with a rated capacity of 170 m^3/d. It comprises two separate treatment units; each consists of a primary settling/sludge storage, a four-stage RBC unit, and a secondary clarifier. Phosphorus is removed chemically with dual injection into the first and third stages of the RBC. Secondary effluent is discharged to a subsurface absorption trench bed. Sludge is hauled off-site for further treatment.

RBC-2 Facility

The RBC-2 Facility is located in Southern Ontario, and it consists of three packaged RBC units (RBC No.1, RBC No.2, and RBC No.3) with a total rated capacity of 150 m^3/d. Each RBC system includes one primary settling tank with sludge storage, a rotating contactor, an intermediate clarifier, a denitrification chamber receiving carbon dosage, and a final clarifier. RBC No.1 and RBC No.2 work in parallel at a combined rated capacity of 100 m^3/d, while RBC No.3 operates separately. The effluents are discharged to subsurface disposal leaching beds. The sloughed biomass is returned to the primary clarifier for co-thickening. The co-thickened primary sludge (PS) and the sloughed biomass are hauled to another WWTP for further treatment.

RBC-3 Facility

The RBC-3 plant has a rated capacity of 270 m^3/d and discharges its effluent to a tributary in southwestern Ontario. The treatment stages include a primary sedimentation tank and four-stage biological support media, a secondary clarifier, and chemical dosing at the final stages of the RBC for phosphorus removal. Effluents of the secondary clarifier go through a tertiary filtration system consisting of buoyant granular media before UV disinfection. Sludge is hauled off-site for proper disposal.

SBR-1 Facility

The SBR-1 Facility is located in Southern Ontario with an existing rated capacity of 291 m^3/d (two out of four phases with a total capacity of 844 m^3/d). It consists of an SBR system with tertiary sand filters discharging to subsurface disposal tile beds. Chemical phosphorus precipitation and external carbon dosing are applied. Waste sludge is stored in holding tanks before haulage.

SBR-2 Facility

SBR-2 is located in Southern Ontario and consists of an SBR system with fixed cloth media filter discharging to subsurface tile beds with an existing capacity of 60 m^3/d (one out of three phases with a total capacity of 140 m^3/d). The treatment steps include a chemical dosing system for phosphorus removal, pH adjustment, and carbon dosing to the SBR system. Sludge is hauled by trucks.

MBR Facility

The MBR Facility considered in this study is located on the north shore of Lake Erie with a rated capacity of 500 m^3/d (currently operating at around 6% of rated capacity). The plant employs microfiltration technology. The preliminary works consist of fine screens, and the biological treatment includes two aeration tanks in series equipped with fine bubble aeration followed by membrane tanks that serve as additional aerobic treatment and house the membrane filters for solid-liquid separation. Ultraviolet lamps disinfect treated effluent. Waste sludge is dewatered via a sludge press.

Lagoon Facility

The Lagoon Facility consisted of three aerated lagoons operated in series with a capacity of 2,500 m^3/d. Coagulant was injected to provide precipitation of phosphorus in the lagoon. Sand filtration was added to this facility with coagulant addition and UV disinfection, which was only required during the summer months (May 15 – September 15). The plant's receiving water body is a bay of Lake Huron within Ontario. It is worth mentioning that this plant was upgraded to an MBBR system preceding the aerated waste stabilization lagoons with an expansion to a rated capacity of 4,400 m^3/d.

EAAS Facility

The EAAS Facility is located in an island of Lake Huron in Ontario. The sewage treatment plant has a rated capacity of 640 m^3/d and 2,160 m^3/day at average and peak flow, respectively. The treatment train consists of coarse bar screens, grit chambers, extended aeration tanks with hydraulic retention time (HRT) ~26 hours designed for nitrification, secondary clarifiers, and chemical dosing for phosphorus removal. Constructed wetlands provide polishing of secondary effluent before discharge to a conservation wetland.

Energy performance indicators

Performance indicators (PIs) are means to facilitate benchmarking of WWTPs (Balmér & Hellström 2012). Recommended in ISO 50001 standards, energy PIs provide quantitative performance metrics that relate energy use, in terms of the application of energy, to energy consumption, expressed in the quantity of energy (Silva & Rosa 2015). PIs are defined as ratios between variables; the numerator expresses the PI objective, and the denominator represents one dimension of the system (Balmér & Hellström 2012; Silva & Rosa 2015). Energy performance in WWTPs is commonly expressed in terms of influent and effluent quality and/ or quantity, pollutant load, plant size and operation (Di Fraia *et al.* 2018). In this work, four main energy key performance indicators (KPIs) were chosen based on the available data in the WWTPs and relate the overall electric energy consumption to the volume of treated wastewater, the served population equivalent, the biochemical oxygen demand (BOD) load removed, and the total suspended solids (TSS) load removed as shown in Equations (1)–(4). It should be noted that the definitions and equivalences of PE vary among countries. This study calculated PE based on BOD, considering 60 g BOD/PE/d (Longo *et al.* 2016).

$$KPI_1 = \frac{electric\ energy\ consumption}{volume\ of\ treated\ wastewater} \quad [kWh/m^3] \tag{1}$$

$$KPI_2 = \frac{electric\ energy\ consumption}{served\ PE} \quad [kWh/PE\ year] \tag{2}$$

$$KPI_3 = \frac{electric\ energy\ consumption}{BOD\ load\ removed} \quad [kWh/Kg\ BOD_{removed}] \tag{3}$$

$$KPI_4 = \frac{electric\ energy\ consumption}{TSS\ load\ removed} \quad [kWh/Kg\ TSS_{removed}] \tag{4}$$

The energy performance is defined based on the removal efficiency of a specific pollutant or the volume of wastewater treated (representation of loading). As part of the performance investigation, removal rates were calculated as shown in Equation (5):

$$R\ (\%) = \left(\frac{Ci - Ce}{Ci}\right) \times 100 \tag{5}$$

where R is the removal efficiency (%); C_i is the average influent concentration in mg/L; and C_e is the average effluent concentration in mg/L

Evaluation of the reliability of WWTPs

The reliability of a system can be defined as 'the probability of achieving adequate performance for a specific period of time under certain conditions' or as 'the ability to perform the specified period of time under specified operation requirements free from failure' as cited in Niku *et al.* 1979. For a WWTP, the reliability level is defined in terms of the performance of a WWTP as the percentage of time at which the expected effluent concentrations comply with specific effluent standards or treatment targets, where a full reliability is achieved if the effluent quality as stipulated by the regulations are not exceeded (Oliveira & Von Sperling 2008; Messaoud *et al.* 2013). Yet the occasional failure of a WWTP in meeting a specific effluent quality parameter is inevitable due to the uncertainties in design and operation. Thus, reliability should be based on some probability of failure that can be accepted.

A well-documented methodology in the literature that incorporates the concept of coefficient of variation (*CV*) and the coefficient of reliability (*COR*) was developed by (Niku *et al.* 1979) to relate the mean design or operational values to the standards that must be achieved on a probability basis. The method was designed to model data according to a lognormal distribution, which was found to be the most widely applicable for water quality and consistently yielding a good fit for the effluent quality data (Niku *et al.* 1979; Oliveira & Von Sperling 2008; Messaoud *et al.* 2013). This study determined the percentage of compliance with the discharge standard (i.e., reliability level) based on the probability distribution of the variability given the WWTP effluent quality data (BOD, TSS, TAN, NH_3-N, TP, etc.) using the relation developed by (Niku *et al.* 1979) that considered the *CV*, Equation (6):

$$Z_{1-\alpha} = \frac{\ln X_s - \left[\ln m_x' - \frac{1}{2}\ln\left(CV^2+1\right)\right]}{\sqrt{\ln\left(CV^2+1\right)}} \tag{6}$$

where $Z_{1-\alpha}$ is the standardized normal variate corresponding to the probability of no exceedance at a confidence threshold of (*1-α*) obtained from standard normal variate tables or determined from Excel NORM.S.INV function; α is significant level (i.e., the probability of failure of meeting standards; X_s is the effluent concentration as specified by the discharge standard in mg/L; m_x' is the mean effluent concentration (actual values) in mg/L; and CV is the coefficient of variation (standard deviation divided by mean) in mg/L.

The *COR* relates the values of the mean design concentrations to the standard to be achieved, on a probability basis as shown in Equation (7) (Oliveira & Von Sperling 2008):

$$m_x = (COR)X_s \tag{7}$$

where m_x is the mean effluent concentration for a selected treated quality parameter in mg/L; and *COR* is the coefficient of reliability.

The *COR* was calculated using the following equation, Equation (8), (Niku *et al.* 1979):

$$COR = \sqrt{CV^2+1} \times exp\left\{-Z_{1-\alpha}\sqrt{\ln\left(CV^2+1\right)}\right\} \tag{8}$$

In this study, by knowing the variability of plant performance for the effluent standards of interest, the average effluent quality that must be maintained to meet a standard with some predetermined reliability level (i.e., probability) was evaluated if a WWTP keeps the same operating conditions. For illustration purposes, the mean effluent concentrations were determined based on a reliability level of 95% (i.e., the plant complies with the standards 95% of the time).

Data analysis

Energy and performance data from the eight WWTPs were obtained directly from the WWTPs operational records and broader public sector (BPS) reporting data. To make the KPIs as comparable as possible, calculated KPIs should, whenever possible, be quantitatively adjusted for local differences. Performance data obtained from the plant included the wastewater parameters as specified by the Environmental Compliance Approval (ECA) or the Certificate of Approval (CoA) of each WWTP. Energy consumption in the selected WWTPs varies based on the treatment processes involved, the treated wastewater quality requirements for each WWTP as stated in their respective ECA or CoA, as well as the operation and maintenance practices applied (Silva & Rosa 2015). The monitoring program of influent and effluent water quality parameters, sampling methods, frequency, and effluent limits and objectives are detailed in Tables 1 and 2.

It is to be noted that data collected from small WWTPs are not as extensive as those collected from large WWTPs due to the limited resources of the small plants. This may explain the lack of performance studies reported in the literature about small plants. Attempts were made in this study to optimize the benefits from additional data provided by the contractor of the plants. It is worth noting that the lagoon plant was upgraded to include MBBR before stabilization lagoons. For the sake of the analysis here and based on the available data, the energy analysis was conducted based on the exclusive lagoon

Table 1 | Monitoring program of influent and effluent parameters for the different WWTPs as per the ECA

Facility	Monitoring Location	Parameters measured	Sample type	Frequency
RBC-1 Facility	Influent	BOD_5, TSS	Grab	Monthly
		TP	Composite	Monthly
	Effluent	$CBOD_5$, TSS, pH, temperature,	Grab	Monthly
		TP	Composite	Monthly
RBC-2 Facility	Influent	BOD_5, TSS, TP, TAN, nitrate, nitrite, TKN, temperature, pH	Grab	Quarterly
	Effluent	$CBOD_5$, TSS, TP, TAN, nitrate, nitrite, TKN, pH, *E. coli*, temperature	Grab	Monthly
RBC-3 Facility	Influent	BOD_5, TSS, TP, TKN, pH, temperature	Not specified	Monthly
	Effluent	$CBOD_5$, TSS, TP, TAN, DO, *E. coli*, pH, un-ionized ammonia	Not specified	Monthly
SBR-1 Facility	Influent	BOD_5, TSS, TP, TKN,	Composite	Monthly
		pH	Grab	Monthly
	Effluent	$CBOD_5$, TSS, TAN, NO_3-N	Composite	Monthly
		TP	Composite	Weekly
		pH, temperature	Grab	Weekly
SBR-2 Facility	Influent	BOD_5, TSS, TP, TKN, total petroleum hydrocarbons (TPH)	Grab	Quarterly
	Effluent	$CBOD_5$, TSS, TP, TAN, NO_3-N, chloride, pH	Grab	Monthly
		Total VOCs, scan of metals, TPH	Grab	Annually
MBR Facility	Influent	BOD_5, TSS, TP, TKN	Composite	Monthly
	Effluent	$CBOD_5$, TSS, TP, TAN	Composite	Weekly
		E. coli, pH, temperature	Grab	Weekly
Lagoon Facility	Influent	BOD_5, TSS, TP, TKN	Grab	Monthly
	Effluent	$CBOD_5$, TSS, TP, TAN	Composite	Biweekly
		E. coli, pH, temperature	Grab	Biweekly
EAAS Facility	Influent	BOD_5, TSS, TP, TKN	Composite	Monthly
	Effluent	$CBOD_5$, TSS, TP, TAN	Composite	Weekly
		pH, temperature	Grab	Weekly
		un-ionized ammonia	Calculated	Weekly

configuration. However, the reliability analysis was performed using the data available after the upgrade to MBBR. A reference was made to the type of technology used in the analysis throughout this study.

The calculated KPIs are based on the energy consumption and performance data over a period of 12 months, where the mean influent flow, the mean concentrations of raw and treated wastewater, and the mean removal efficiencies associated with the four treatment technologies were used to calculate the KPIs. The data and operational records were available for different years for each plant. Therefore, each of the plants was analyzed individually then gathered in groups as per the technology applied for the sake of comparison (e.g., RBC group, SBR group, etc.). The study mainly focused on WWTPs in small communities where limited monitoring and sampling programs within the treatment process were observed. The valid data points vary from a plant to another. However, an average sampling of 13 data points per year was available and used for the analysis. The effluent quality standards varied among the treatment facilities according to CoA or ECA (Table 2). However, conventional contaminants removal such as BOD and TSS were common in all WWTPs' effluent requirements. To accurately capture the energy consumption in relation to the wastewater treatment performance indicators, analysis was done based on the availability of both energy data and performance data for the same period. For example, data points from 2017 were chosen for the RBC-1 Facility, RBC-2 Facility, RBC-3 Facility, EAAS Facility, and MBR Facility WWTPs, while data for 2020 was used for SBR-1 Facility and SBR-2 Facility WWTPs.

RESULTS AND DISCUSSION

Energy KPIs

Energy consumption data were collected as related to the operation (flow rate) and wastewater characteristics (BOD, TSS, TN, and TP). The PE was calculated based on 60 g BOD/person/d in each case. Figure 1 illustrates the energy comparison (electric energy KPIs) based on the volume of waste treated, PE, amount of BOD removed, and amount of TSS removed,

Table 2 | Effluent parameters objectives and limits as per the ECA

	Concentrations in mg/L unless otherwise indicated			
Plant (Technology)	**Effluent parameters limits**		**Effluent parameters objectives**	
RBC-1 Facility (RBC)	CBOD$_5 < 15$ TSS < 15 TP < 1 $6.0 < \mathrm{pH} < 9.5$		CBOD$_5 < 10$ TSS < 10 TP < 0.8 $6.5 < \mathrm{pH} < 9.0$	
RBC-2 Facility (RBC)	N/A		CBOD$_5 < 20$ TSS < 20 T$N < 19$	
RBC-3 Facility (RBC)	CBOD$_5 < 10$ TSS < 10 TP < 0.3 TP, $_{\text{Freezing*}} < 0.8$ TA$N < 3$ TAN, Freezing* < 5 DO > 4 *E.coli* < 200 org/mL $6.0 < \mathrm{pH} < 9.5$		CBOD$_5 < 5$ TSS < 5 TP < 0.2 TP, $_{\text{Freezing*}} < 0.5$ TAN < 2 TAN, Freezing* < 4 DO > 5 *E.coli* < 150 org/mL $6.5 < \mathrm{pH} < 8.5$	
SBR-1 facility (SBR)	CBOD$_5 < 15$ TSS < 15 TAN + NO$_3$-$N < 4.2$ $6.0 < \mathrm{pH} < 9.5$		CBOD$_5 < 12$ TSS < 12 TAN + NO$_3$-$N < 3.5$ $6.5 < \mathrm{pH} < 8.5$	
SBR-2 facility (SBR)	CBOD$_5 < 10$ TSS < 10 TP < 5 TAN + NO$_3$-N < 10		CBOD$_5 < 5$ TSS < 7 TP < 2 TAN + NO$_3$-N < 5	
MBR facility (MBR)	BOD$_5 < 10$ TSS < 10 TP < 0.3 TAN < 1.5 TAN, $_{\text{Freezing*}} < 4$ *E.coli* < 100 cfu/100 mL		BOD$_5 < 5$ TSS < 5 TP < 0.2 TAN < 1 TAN, $_{\text{Freezing*}} < 3$ *E.coli* < 150 cfu/100 mL	
Lagoon facility (Lagoon/MBBR)	CBOD$_5 < 20^{\dagger}$ TSS $< 24^{\dagger}$ TP $< 0.5^{\dagger}$ N/A† N/A† $6.0 < \mathrm{pH} < 9.5$ *E.coli* < 200 cfu/100 mL (geometric mean density from May 15 -September 15)	CBOD$_5 < 15^{\ddagger}$ TSS $< 15^{\ddagger}$ TP $< 0.3^{\ddagger}$ TAN $< 3^{\ddagger}$ TAN, $_{\text{Freezing**}} < 6^{\ddagger}$	CBOD$_5 < 15^{\dagger}$ TSS $< 15^{\dagger}$ TP $< 0.3^{\dagger}$ TAN $< 3^{\dagger}$ TAN, $_{\text{Freezing**}} < 8^{\dagger}$ $6.5 < \mathrm{pH} < 8.5$	CBOD$_5 < 10^{\ddagger}$ TSS $< 10^{\ddagger}$ TP $< 0.15^{\ddagger}$ TAN $< 3^{\ddagger}$ TAN, $_{\text{Freezing**}} < 6^{\ddagger}$
EAAS facility (EAAS)	CBOD < 25 TSS < 25 TP < 1.5 TAN < 5.0 $6.0 < \mathrm{pH} < 9.5$		CBOD < 15 TSS < 15 TP < 1 TAN < 3.0 $6.5 < \mathrm{pH} < 9.0$	

*Freezing Limit is from December 1 to April 30.

**Freezing Limit is from November 1 to April 30.

†ECA limits and objectives from January 1, 2017 – November 22, 2017.

‡ECA limits and objectives from November 23, 2017 – December 31, 2017.

respectively. The specific power consumption values obtained in this study are comparable to those reported by (Mizuta & Shimada 2010) for WWTPs in Japan which ranged from 0.44 to 2.07 KWh/m^3 for oxidation ditch plants and from 0.30 to 1.89 KWh/m^3 for conventional activated sludge plants without sludge incineration, where the variations were attributed to the difference in the scale of plants rather than to the type of treatment processes. According to ISO 50001 (ISO 2011), energy performance is determined by measurable results correlated to energy efficiency, energy use, and energy consumption,

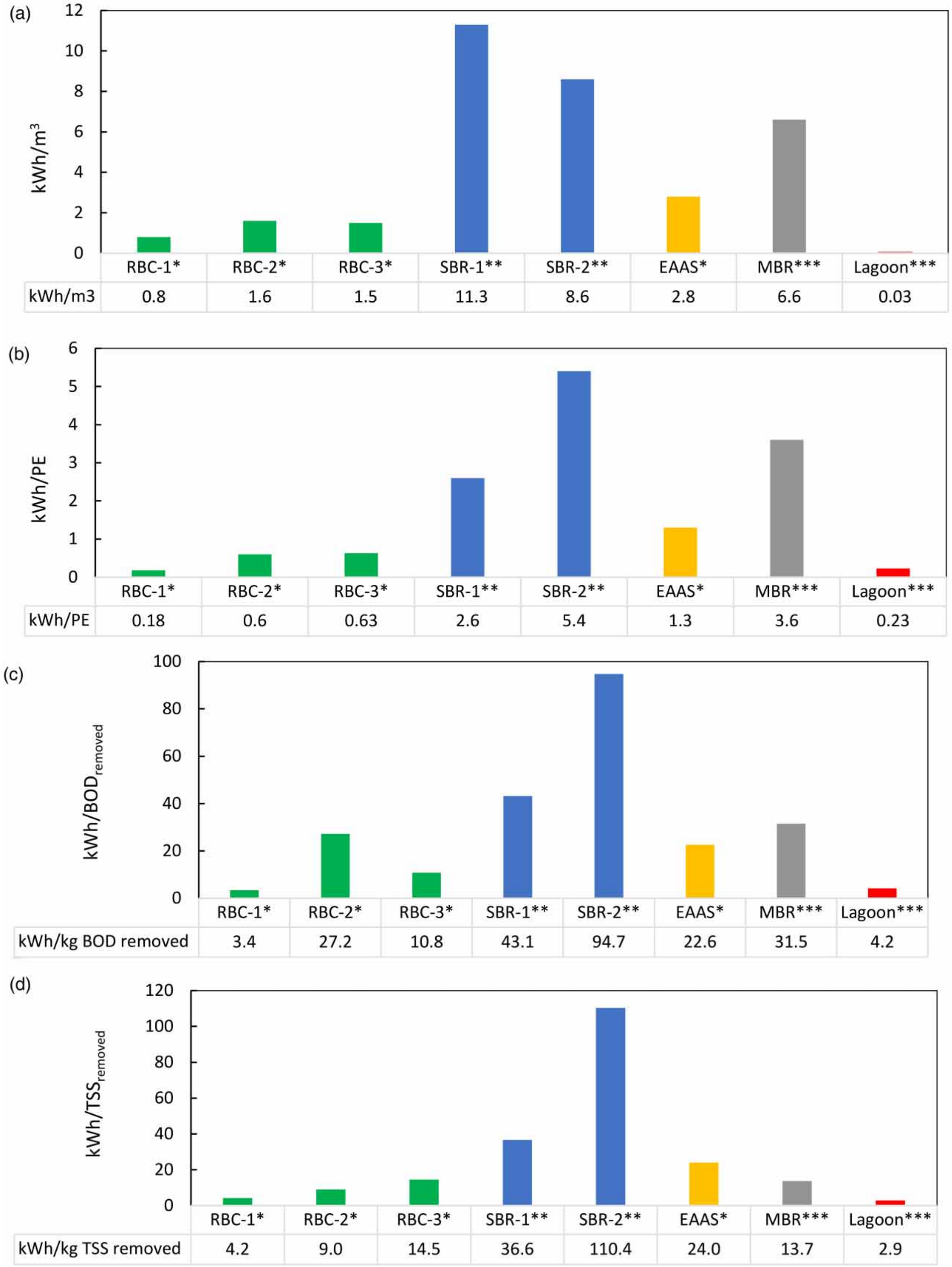

Figure 1 | Energy comparison based on: (a) volume of wastewater treated, (b) PE, (c) amount of BOD removed, and (d) amount of TSS removed. * 2017 energy data and 2017 performance parameters. ** 2020 energy data and 2020 performance parameters. *** 2017 energy data and 2019 performance parameters. **** 2013 energy data and 2013 performance parameters.

the latter expressing the quantity of energy. Energy analyses indicate that lagoons followed by RBC technology consumes less energy per unit performance indicator compared to other technologies considered in this study. The RBC-1 Facility, being a small plant employing the RBC, showed the lowest energy consumption among the three RBC facilities considered. It is worth noting that the two SBR facilities and the EAAS plant considered in this study showed relatively high energy consumption. The elevated energy consumption in the EAAS plant can be attributed to the energy requirements for aeration in the extended aeration tanks, which were designed for nitrification with an HRT of 26 hours. Similar results were reported in a cost estimation and an economical evaluation of three configurations of activated sludge processes; namely, conventional activated sludge (CAS), SBR, and EAAS. It was found that the energy costs for EAAS was the highest followed by the SBR, while WWTP containing CAS was the most cost effective (Jafarinejad 2017). However, when comparing the KPI based on the volume of treated wastewater (kWh/m^3) with the figures reported in the literature for various processes, results obtained in this study are at least 4 times higher in the EAAS plant (2.8 kWh/m^3), 13–18 times higher in the SBR plants (8.6 and 11.3 kWh/m^3) when compared to the estimated figures for activated sludge processes (0.33–0.6 kWh/m^3), 2–4 times higher for the RBC plants (0.8, 1.6, and 1.5 kWh/m^3) when compared to treatments such as tricking filters (0.18–0.42 kWh/m^3), and the MBR plant (6.6 kWh/m^3) had over 3 times higher energy requirement when compared to advanced wastewater treatment processes, which were reported to reach 2 kWh/m^3 (Gude 2015; Guven *et al.* 2019). These figures showed that the energy requirements reported in the literature underestimate the energy consumed in small WWTPs.

Performance reliability

In this study, a methodology was incorporated that allowed for the evaluation of individual biological process performance data to make an estimation of the overall treatment reliability for the entire facility, for water quality parameters such as BOD, TSS, TN, and TP, which may be removed to levels that are specified by the regulatory agency in the province of Ontario. It is believed that many WWTPs in small communities may not have the resources to participate in true benchmarking exercises; nevertheless, incorporating the concepts of KPIs in the process evaluation can be beneficial in providing a comparative assessment of performance. Equations (5)–(8) were used for determining *R* (%), *CV*, and *COR*, in terms of the compliance of effluent BOD, TSS, TN and TP with discharge standards. In total, records from the eight WWTPs were analyzed. The mean influent flow, the mean concentrations of raw and treated wastewater, and the mean removal efficiencies associated with the four treatment technologies were determined.

The mean influent flow, the mean concentrations of raw and treated wastewater and the mean removal efficiencies associated with the five treatment technologies are presented in Table 3. In general, some variability was noticed in the effluent concentrations and in the removal efficiencies, considering the analyzed constituents and treatment technologies. Effluent concentrations from urban WWTPs are inherently variable due to the dynamic nature of the influent loads and environmental characteristics (e.g., temperature, pH, DO) in each process considered in this study. The extent of effluent variability depends on the behavior of the influent loads and environmental factors, and the treatment process itself, where operating at longer HRTs typically provides higher buffering capacity when compared to compact treatment systems which are more susceptible to process instabilities due to the fluctuations in influent characteristics (Oliveira & Von Sperling 2008). In the WWTPs investigated in this study, the average removal efficiencies for BOD exceeded 90% for most plants, except for RBC-2 Facility (RBC-2.1 86%) and EAAS Facility (83%). Similarly, all plants were effective in removing TSS, with average removal efficiencies above 90%, except RBC-2.1, RBC-2.3, and EAAS Facility, where the removals were 85, 88, and 87%, respectively. Chemical phosphorus removal was applied in all plants resulting in effective treatment except in RBC-2 Facility, where TP removal is not required as per the ECA.

Tables 4 and 5 present the reliability analysis conducted on the performance data of each WWTPs. The design concentrations necessary to meet the prevailing discharge standards and the expected compliance percentages have been calculated from the *COR* obtained. The results showed that some plants, under the observed operating conditions, were able to present reliable performances (Figure 2). In general, the treated effluent characteristics did not exceed the prescribed effluent quality limits set by the regulatory agency in Ontario. However, comparatively, the RBC-2 Facility RBC plant showed poor reliability levels in terms of TSS, while MBR Facility showed a very high level of reliability for TSS (>99%), average TP (84%), and BOD data was insufficient to conclude reliability levels. RBC-3 Facility plant showed very high reliability levels (>97%), except for TSS (<80%). Despite the variabilities found in some of the RBC-based plants, it has been reported that RBCs generally provide stable effluent quality compared to other technologies such as activated sludge, trickling filters, and high performance aerated filters (Bruce & Graham 2019).

The *COR* values of the wastewater parameters of interest, taking into consideration the *CV* of the WWTP in operation, have been calculated for a level of reliability of 95% (Tables 4 and 5). The *CV* values differed for different treatment technologies, with relatively lower effluent variability observed for the RBC WWTPs. However, it should be noted that low *CV* values and,

Table 3 | Removal efficiencies for different WWTPs

Technology			**RBC**			**SBR**			**MBR**	**MBBR**	**EAAS**
			RBC-2 Facility (2013–2020)								
Plant		**RBC-1 Facility (2017)**	**RBC 2.1**	**RBC 2.2**	**RBC 2.3**	**RBC-3 Facility (2017)**	**SBR-1 Facility (2017)**	**SBR-2 Facility (2017)**	**MBR Facility (2019–2020)**	**Lagoon Facility (2017)**	**EAAS Facility (2020)**
Avg. flow (m^3/d)		53.4	42.7	42.7	35.7	103.1	241.2	23.4	30.4	1,721.7	175.50
BOD (mg/L)	Inf.	143.3±53.0	99.6±42.0	273.8±332	124.3±69	143.3±53.0	325.7±180.0	186.0±84.0	213±70.0	146.4±72.0	98.80±99.40
	Eff.	4.1±2.50	14.2±43.0	13.4±10.0	10.9±15	4.1±2.50	5.1±4.0	2.5±1.0	2±0.0	4.1±3.50	5.60±6.0
	% rem.	97.0±2.0	86.0±63.0	95.0±10.0	91.0±18.0	97.0±2.0	98.0±1.0	99.0±1.0	99.0±0.40	97.0±2.0	83.20±44.0
TSS (mg/L)	Inf.	112±50	112.0±75.0	251.7±300	144.9±102	112±48.0	248.8±325.0	166.9±136.0	325.1±226.0	117.5±52.0	154.0±140.0
	Eff.	7.9±4.0	16.9±19.0	14.8±16.0	17.9±23.0	7.8±4.0	7.0 + 6.0	5.5±3.0	2.6±2.0	6.8±8.0	11.0±9.0
	% rem.	93.0±7.0	85.0±22.0	94.0±18.0	88.0±21.0	93.0±11.0	97.0±3.0	94.0±8.0	99.0±1.0	94.0±9.0	87.0±11.0
TP (mg/L)	Inf.	4.59±1.25	6.02±1.0	7.41±4.0	7.10±2.0	4.59±1.20	11.50±23.0	7.27±2.0	6.74±2.0	2.10±1.0	2.48±2.0
	Eff.	0.11±0.06	4.69±0.60	4.57±1.0	4.62±1.0	0.11±0.10	0.26±0.40	0.78±1.0	0.20±0.13	0.08±0.02	0.14±0.10
	% rem.	97.50±1.0	22.0±15.0	38.0±20.0	35.0±15.0	98.0±1.0	98.0±2.0	89.0±11.0	97.0±2.0	96.0±2.0	90.0±11.0

Table 4 | Comparison of expected percentage of compliance for RBC plants

				RBC-2 Facility												
	RBC-1 Facility			RBC No.1			RBC No.2			RBC No.3			RBC-3 Facility			
Plant Parameter	CBOD5	TSS	TP	CBOD5	TSS	TN	CBOD5	TSS	TN	CBOD5	TSS	TN	CBOD5	TSS	TN	TP
$Z_{1\text{-}\alpha}$	2.61	1.67	4.96	0.98	0.14	N/A	0.87	0.25	N/A	0.80	0.06	N/A	1.88	0.76	2.45	4.47
Reliability Level (%)	100.0	95.0	100.0	84.0	56.0	N/A	81.0	60.0	N/A	79.0	52.0	N/A	97.0	78.0	99.0	100.0
Considering 95% reliability																
α (95%)	0.05	0.05	0.05	0.05	0.05	N/A	0.05	0.05	N/A	0.05	0.05	N/A	0.05	0.05	0.05	0.05
$Z_{1\text{-}\alpha}$	1.645	1.645	1.645	1.645	1.645	N/A	1.645	1.645	N/A	1.645	1.645	N/A	1.645	1.645	1.645	1.645
CV	0.61	0.47	0.48	2.06	0.83	N/A	0.72	0.75	N/A	1.00	0.91	N/A	0.61	0.47	3.82	0.49
COR	0.46	0.53	0.52	0.28	0.40	N/A	0.42	0.42	N/A	0.36	0.38	N/A	0.46	0.53	0.26	0.52
X_s	15.0	15.0	1.0	20.0	20.0	N/A	20.0	20.0	N/A	20.0	20.0	N/A	10.0	10.0	5.0	0.8
$m_x = Xs \times COR$	6.96	7.94	0.52	5.51	7.92	N/A	8.48	8.30	N/A	7.18	7.56	N/A	4.64	5.30	1.29	0.42
Year of data	2017	2013–2020	2017													

Table 5 | Comparison of expected percentage of compliance for SBR, MBBR, MBR, and EAAS plants

Technology	**SBR**							**MBBR**			**MBR**			**EAAS**		
Plant	**SBR-1 Facility**			**SBR-2 Facility**				**Lagoon Facility**			**MBR Facility**			**EAAS Facility**		
Parameter	**CBOD5**	**TSS**	**TAN + NO_3–N**	**CBOD5**	**TSS**	**TP**	**TAN + NO_3–N**	**CBOD5**	**TSS**	**TP**	**CBOD5**	**TSS**	**TP**	**CBOD5**	**TSS**	**TP**
$Z_{1\text{-}}\alpha$	1.93	1.40	0.08	3.96	1.33	2.57	1.77	2.47† 2.39	1.80† 2.91‡	6.36† N/A‡	_	3.23	0.99	2.1	1.6	4.0
Reliability Level (%)	97.0	92.0	53.0	100.0	91.0	99.0	96.0	99.3† 99.2‡	96.4† 99.8‡	100.0† N/A‡	N/A	100.0	84.0	98.0	94.0	100.0
Considering 95% reliability																
α (95%)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$Z_{1\text{-}}\alpha$	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645
CV	0.75	0.84	2.47	0.38	0.61	1.06	2.72	0.86† 0.71‡	1.13† 0.47‡	0.30† 0.0‡	N/A	0.65	0.67	1.0	1.0	0.7
COR	0.41	0.39	0.26	0.59	0.47	0.35	0.26	0.38† 0.43‡	0.34† 0.53‡	0.65† 1.0‡	N/A	0.44	0.44	0.4	0.4	0.4
X_s	15.0	15.0	4.2	10.0	10.0	5.0	10.0	15.0†	15.0†	0.3†	N/A	15.0	0.3	25.0	25.0	1.5
m_x	6.23	5.88	1.12	5.87	4.66	1.75	2.63	7.68† 6.45‡	8.11† 7.94‡	0.33† 0.3‡	N/A	6.72	0.13	8.87	8.93	0.64
Year of data	2017			2017				2017			2019–2020			2017–2020		

†Average levels of compliance with discharge limits stipulated by ECA from January 1, 2017 – November 22, 2017.

‡Average levels of compliance with discharge limits stipulated by ECA from November 23, 2017 – December 31, 2017.

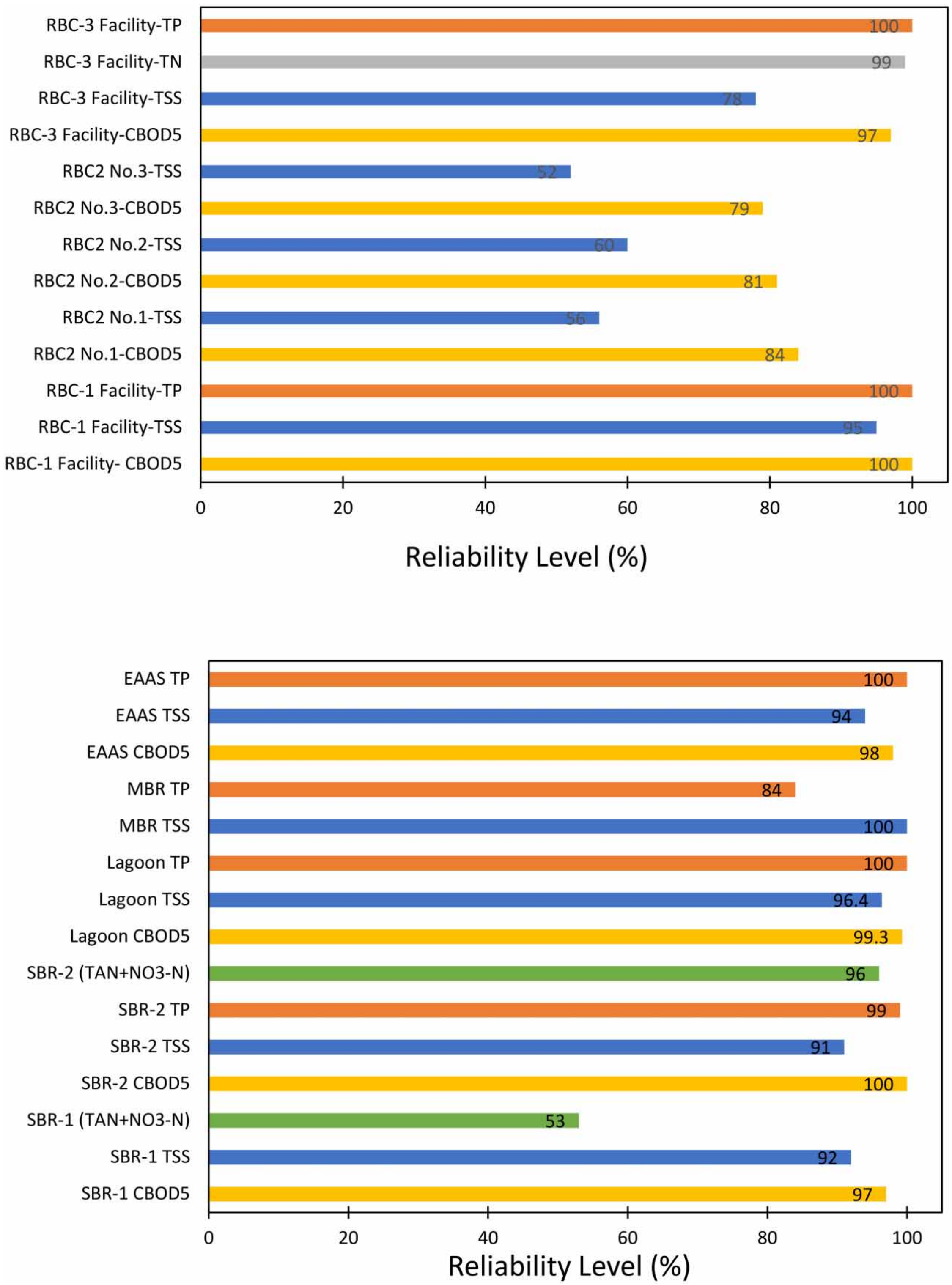

Figure 2 | Reliability level for: (a) RBC plants and (b) SBR, Lagoon, MBR, and EAAS plants.

consequently, high *COR* values do not necessarily imply a good performance but simply a more stable operating condition. Low *COR* values imply the need for lower design effluent concentrations since these will be obtained by multiplying the *COR* by the discharge standard value to be achieved (Oliveira & Von Sperling 2008).

CONCLUSION

The proposed KPI-system provides a helpful tool for the performance assessment of WWTPs. A general overview of the energy consumption for different wastewater treatment technologies employed in small communities showed that lagoons, followed by RBCs had a unique advantage in terms of energy consumption, as indicated by energy KPIs. The SBR-based WWTPs showed the highest energy consumption compared to other technologies. Despite the low energy consumption, the lagoon-based plant investigated in this study was upgraded to an MBBR system to meet stricter effluent quality standards. The increase in energy prices provides stronger inducements for energy efficiency measures in the wastewater treatment plants.

The reliability of different WWTPs was predicted using probabilistic methods, where the WWTP's performance was expressed as a function of mean values and effluent variability. In stable operation conditions, the low values of *COR* would imply the need for lower design effluent concentrations. A well-maintained RBC plant considered in this study showed outstanding reliability levels (>95%) for BOD, TAN, and TSS. However, four RBC units in two of the facilities considered in this study showed low reliability in terms of TSS removal (52–78%), which was mainly attributed to poor maintenance, inconsistencies in sludge hauling or units' failure. It is crucial to perform regular sludge removal in RBC clarifier units to enhance TSS removal. However, to achieve reliable TSS removal, routine sampling and monitoring of each unit treatment could provide better process control and early warning of any anticipated equipment failures. The application of the reliability concept can also be used in the setting of wastewater discharge standards, determining the treatment objectives, and designing the plant to produce a mean effluent concentration below the discharge limits.

The study also highlighted a huge opportunity to adopt innovative solutions and promote efficiency and optimization within the WWTPs to reduce the energy intensity and thus reducing the overall operating cost. Furthermore, municipalities should encourage energy monitoring and tracking to collect, analyze, and track the energy intensity that can be used in the business case for any electro-mechanical asset renewal project. Quantification of energy and GHG savings as a result of any capital project should be a standard process.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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