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# An Innovative Remote-Controlled Device for Reducing Energy Consumption and GHG Emissions From Water Resource Recovery Facilities

Cecilia Caretti[1], I. Ducci[1], F. Spennati[2], P. Aloisi[3], M. Spizzirri[4], S. Dugheri[5], and R. Gori[1]

*1. Civil and Environmental Engineering Department, University of Florence, Italy*

*2. Consorzio Cuoiodepur SpA, Italy*

*3. West Systems Srl, Via Mazzolari 25, 56025 Pontedera (PI), Italy*

*4. Acea Spa, P.le Ostiense 2, 00154 Rome, Italy*

*5. Experimental and Clinical Medicine Department, University of Florence, Italy*

**Abstract:** Water Resource Recovery Facilities (WRRFs) are sources of direct emissions of greenhouse gases (GHGs) and volatile organic compounds (VOCs) produced by biological processes and indirect GHG emissions from the energy necessary for operating the treatment processes. The direct emissions also contribute to odour issues of WRRFs. Biological tank aeration accounts for 50-60% of the total energy consumption of WRRFs. The development and implementation of innovative tools for reducing WRRF carbon footprint by optimizing the efficiency of aeration processes are therefore important goals for WRRF environmental sustainability. The innovative solution proposed in this study consists of an automated self-moving prototype (LESSDRONE) for real-time monitoring of the oxygen transfer efficiency (OTE) and GHG emissions of the aerated tanks under operating conditions, and a protocol for converting LESSDRONE measures and specific WRRF data into actions aimed at minimizing carbon footprint and energy demand. The prototype made it possible to independently carry out continuous tests to measure OTE, GHG concentrations, VOCs, odourants and off-gas flow rates throughout entire tanks under different operating conditions. It was therefore possible to assess the spatial and temporal variability of the measured parameters. Based on the results obtained for different airflow rates and dissolved oxygen (DO) concentrations in the tanks, optimal WRRF process conditions and the parameters most affecting GHG emissions and OTE were identified. The benefit of new air diffusive membranes and cleaning processes on aeration efficiency and effectiveness was assessed.

**Key words:** aeration efficiency, energy saving, GHGs, odour, VOCs, WRRFs

## 1. Introduction

GHG emissions from WRRFs can be classified as direct and indirect [1]. Direct emissions derive from biological processes that occur in the plant, while indirect emissions are associated with energy consumption for the treatment processes. Globally, WRRFs contribute about 3% to total GHG emissions [2]. Carbon dioxide ($CO_2$) is produced during biological oxidation of biodegradable organic substance. Nitrous oxide ($N_2O$) emissions from WRRFs are mainly due to nitrification and denitrification processes in which $N_2O$ is an intermediate product [3]. Since the global warming potential (GWP) of $N_2O$ is 298 $CO_{2eq}$ over 100 years, they contribute significantly to WRRF carbon footprint despite the fact that WRRF $N_2O$ emissions are generally low. Methane ($CH_4$) emissions originate mainly in sewer pipes and in sections of WRRFs where

**Corresponding author:** Cecilia Caretti, Ph.D.; research areas: environmental engineering: water and wastewater treatment. E-mail: cecilia@dicea.unifi.it.

anaerobic conditions prevail. However, non-negligible $CH_4$ emissions can also be detected in the oxidative compartments, as aeration favours stripping of dissolved methane coming from other treatment sections, such as anaerobic ones.

WRRFs are also major sources of other air pollutants, such as VOCs and odourants [4, 5]. VOCs include all the odourous compounds generated by degradation of organic matter in wastewater. They can form in the sewer by anaerobic processes and are more readily released into the atmosphere at points of turbulence or due to stripping in aerated treatment tanks. The emissions from urban and/or industrial wastewater treatment plants can be particularly complex and foul-smelling due to the complexity of wastewater. The malodourous emissions associated with wastewater treatment have negative effects on the health of communities living near WRRFs and complaints about air pollution are on the increase [6]. In recent years, the monitoring of odourous emissions has therefore become important in the management of WRRFs.

Energy consumption by WRRFs increases with inlet load and is largely due to the aeration systems of the oxidation tanks [7]. Since aeration is responsible for a large share of indirect emissions, its optimization is crucial for minimizing WRRF carbon footprint. Aerobic activated sludge processes are the most widely used method for urban and industrial wastewater treatment, and optimization of oxygen transfer, for example through correct management (cleaning and/or replacement) of diffusers can significantly reduce plant carbon footprint [8]. Monitoring of direct GHG emissions is also important to assess operational conditions that allow their reduction. The importance of reducing WRRF carbon footprint has been highlighted by the Italian Regulatory Authority for Energy Networks and Environment (ARERA) which introduced the "regulation of technical quality for integrated water services" through indicators that include one related to the carbon footprint of the wastewater treatment service. Reliable tools for measuring aeration system performance can therefore be very useful for WRRF managers.

In this context, the LIFE LESSWATT project (LIFE16 ENV/IT/000486), co-financed by the European Union, has the main objective of designing and implementing an innovative tool to assess and minimize the direct and indirect contributions of oxidation processes to WRRF carbon footprint. The proposed solution includes a prototype (LESSDRONE) for monitoring OTE and GHG emissions during operation, and a protocol that translates the information collected into actions aimed at minimizing WRRF carbon footprint. LESSDRONE also collects oxidation tank off-gas samples to measure VOCs and odour. The project started in October 2017 and will end in November 2021. The project partners are the University of Florence, the Consorzio Cuoiodepur Spa, the University of Ghent, WEST System Srl and the Utilitatis Foundation.

Six measurement campaigns were conducted at the Cuoiodepur WRRF (Tuscany, Italy) for the prototype testing phase and other measurement campaigns are being carried out in five other WRRFs in Italy (Florence, Rome and Reggio Emilia) and the Netherlands (Eindhoven and Tilburg) to evaluate technology transferability and versatility in different contexts. Here we describe the prototype and its functions, and by way of example, the main outcomes of the measurement campaigns at the Cuoiodepur WRRF (OTE and GHG emission results) and at the East Rome WRRF (VOC and odour results).

## 2. Material and Methods

LESSDRONE (Fig. 1) is a device composed of a steel support frame, removable and foldable, bearing six independent inflatable flotation cylinders, one for each arm of the frame. At the center of the frame there is a hood that conveys gases released from the liquid surface into a collection pipe. The upper part of the frame bears a housing for two boxes of the analysis instrumentation and the control/positioning devices.

The gas passes through a condensate collection system and then through four parallel cartridges containing silica gel to remove residual moisture from the sample. It then passes through sensors that measure $CO_2$, $CH_4$, $N_2O$ and $O_2$. The instrument also measures humidity, temperature and gas pressure in the circuits and has a probe for measuring DO and temperature in the mixed liquor. LESSDRONE is powered by eight underwater propellers, each of which can deliver a thrust of approximately 8.2 kgf. The drone can be moved by remote control or can follow a programmed path in the tank set using the Global Positioning System (GPS), parking itself and measuring automatically. The $CO_2$ sensor, based on the principle of infrared absorption, has a measurement range between 0% and 20% with an accuracy of ±0.2% $CO_2$ for measurements between 0% and 8% (typical of WRRF aeration tank off-gases). The $O_2$ sensor, based on optical fluorescence, has a measurement range between 0 and 300 mbar (0-25% $O_2$ partial pressure) and a full-scale (FS) accuracy of ±2%. The $N_2O$ infrared sensor has a measurement range between 0 and 2000 ppm and an accuracy of ±2% FS. The $CH_4$ infrared sensor has a measurement range between 0 ppm and 2000 ppm and an accuracy of ±4% FS.

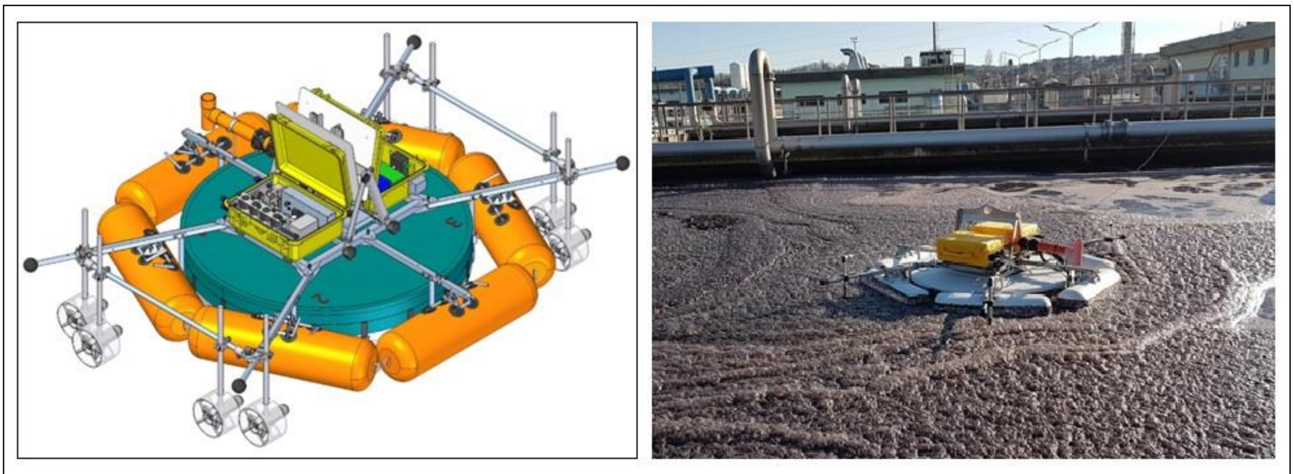

**Fig. 1 3D view of LESSDRONE (left); LESSDRONE in the oxidation tank during a measurement (right).**

LESSDRONE was designed and built to evaluate OTE by the off-gas method [9], which is based on a gaseous phase mass balance of oxygen in the reference gas (atmospheric air) and in the off-gas. During the experimental campaigns, two different tests were carried out: a point test and a stationary test. The point test consists in monitoring several points in the tank (covering at least 2% of tank area) to determine the spatial distribution of OTE, the off-gas flow rate and GHG concentrations. This test is performed with an air flow rate kept as constant as possible to ensure the same conditions in the different sampling points. Sampling time at a given point is set by the operator (generally 5-10 minutes). The stationary test consists in monitoring the temporal variability of the measured data in relation to the different process conditions (inlet loads, air flow, DO, night/day, weekdays/holidays), for a prolonged period (generally at least 7 days), at a fixed point in the tank. In this test, air flow is adjusted automatically according to the ordinary control system.

An aliquot of off-gas captured by the hood can also be conveyed via a silicone tube to inflate nalophan (or tedlar) bags (1-5 liters) outside the tank. These off-gas samples are subsequently analyzed in the laboratory for VOCs (by gas chromatography-mass spectrometry), hydrogen sulphide ($H_2S$, by gas chromatography and pulsed flame photometric detector) and odour units (via portable automatic olfactometer SM100i).

The Cuoiodepur WRRF (850,000 PE, 130 gCOD/d/PE) is at San Miniato (Pisa), a major

European tanning district. The tests were carried out in two of the seven oxidation tanks of the plant (tank no.5 and tank no.6, Fig. 2). The tanks (51 m × 13.5 m) have uneven diffuser distribution. Three zones can be distinguished from the input to the output section: the first with 3.4 diffusers/m$^2$, the second with 2.7 diffusers/m$^2$ and the third with 1 diffuser/m$^2$. The two tanks differ in diffuser age: tank no.5 diffusers were replaced in August 2018, while tank no.6 diffusers were replaced in September 2017. Diffusers are replaced once every 4 years. Six measurement campaigns (on tanks 5 and 6) were carried out from May 2019 to July 2020. Two point tests and one 10-day stationary test were performed for each measurement campaign. During the point tests, measurements were made in nine different points of each tank in order to ensure monitoring of at least 2% of tank area, according to recommendations in the literature [10]. The stationary tests were carried out at a fixed point in the center of the tank. During each campaign, mixed liquor samples were taken at the tank inlets and outlets to determine COD and analyze nitrogen compounds (N-$NH_4^+$, N-$NO_2^-$, N-$NO_3^-$, TN).

The East Rome WRRF is one of the largest in Italy and treats 900,000 PE (about 280,000 m$^3$/day of municipal wastewater). The tests were performed in one of the plant's seven oxidation tanks (Fig. 3). The tank (91 m × 21 m) is divided into three sections of equal area but with different numbers of air diffusers. In January 2021, in order to monitor more than 2% of tank area, 12 points were sampled in three point tests. Off-gas was also sampled in nalophan bags for VOCs, $H_2S$ and odour analysis at six of the 12 measurement points. The 7-day stationary test was run at a central point in the tank.

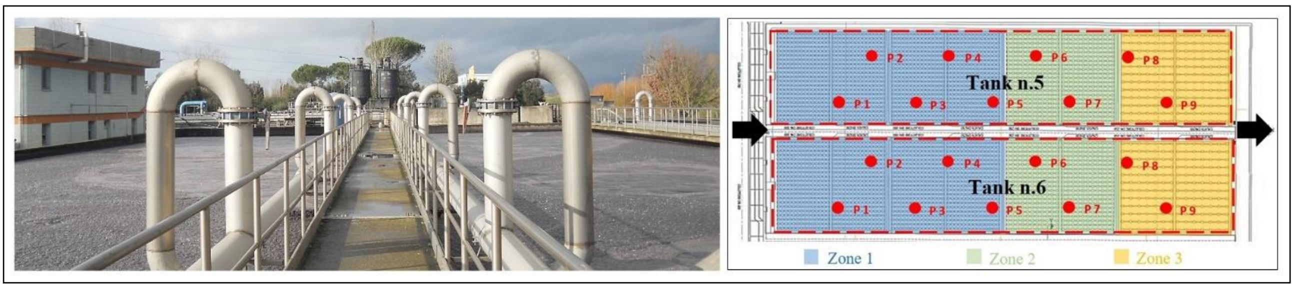


**Fig. 2 Cuoiodepur WRRF oxidation tanks (left); scheme of measuring points and the three different diffuser density zones in the two tanks (right).**

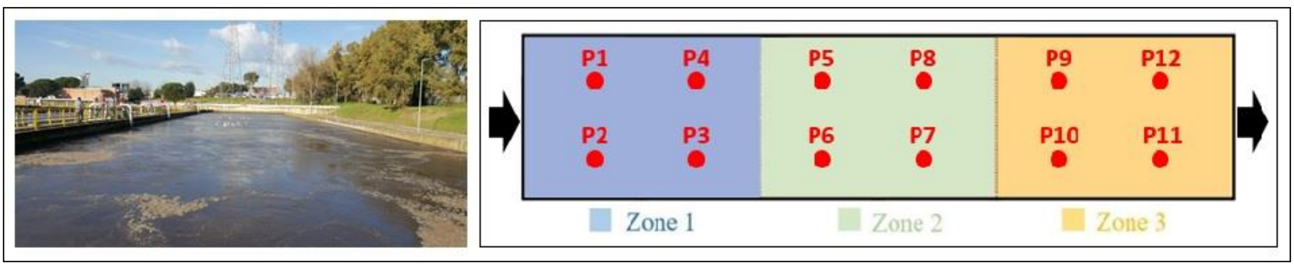


**Fig. 3 East Rome WRRF oxidation tank (left); the measuring points and the three diffuser density zones in the tank (right).**

A protocol for WRRF optimization, focusing on carbon footprint reduction by minimizing energy expenditure and GHG emissions, was developed in parallel with the experimental campaigns. In addition to the experimental data collected by LESSDRONE, the protocol exploits advanced modeling paradigms including: flow sheet biokinetic modelling, computational fluid dynamics (CFD) modeling combined with a biokinetic model and $N_2O$ risk assessment modeling.

## 3. Results and Discussion

The main results of the measurement campaigns carried out at Cuoiodepur WRRF can be summarized as follows. In the point tests, air flow averaged 3.4 $Nm^3/h/m^2$; in tank no.5, air flow was higher at the beginning of the tank and lower at the end, in line with diffuser density, while in tank no.6 higher air flow was recorded in the central zone. The low values at the beginning of this tank were probably due to greater diffuser membrane fouling, which causes larger concentrated pressure drops in this zone. Averaged over the total area of the tank, the air flow calculated by LESSDRONE was about 2200 $Nm^3/h$, very close to the value measured by the air flow meters (about 1900 $Nm^3/h$) installed in the oxidation tanks. Thus LESSDRONE can not only highlight the spatial distribution of air flow in the tanks, but can also assess the total air supplied from the values measured at different points in the tanks. This is important information for plants which do not have air flow meters in each tank, unlike Cuoiodepur.

Average oxygen transfer efficiency under standard conditions in process water (αSOTE) was 30.3% and 28.7% in tank no.5 and tank no.6, respectively. This agrees with the different ages of the diffusers in the two tanks (older membranes are less efficient). The αSOTE per meter of depth lies in the range 5-6% $m^{-1}$, according to the literature [11]. The efficiency of the aeration systems is influenced by wastewater characteristics, for example surfactant concentrations [12], and by WRRF process conditions, and depends above all on air flow rate, sludge retention time (SRT) and total suspended solids (TSS) in the mixed liquor [11, 13]. An air flow increase matches a reduction in OTE since efficiency is affected by bubble dynamics. This was confirmed by most of our experimental results. The relationship between efficiency (αSOTE) and SRT did not emerge, since Cuoiodepur WRRF has a very high SRT (> 40 days) [11]. The influence of surfactants was negligible since their concentrations were very low in inlet wastewater (< 3 mg/l). There was no correlation between αSOTE and TSS concentrations, which were in the range 8.0-12.5 $kg/m^3$.

The average direct $CO_2$ emissions measured during the point tests were 174 $gCO_2/h/m^2$. Differences between emissions from the two tanks were negligible. In both cases the trend followed that of air flow, since off-gas $CO_2$ concentrations were almost uniform within the tanks. The average direct $N_2O$ emissions were 0.02 $gN_2O/h/m^2$, low in both tanks and uniform within the tanks. The average direct $CH_4$ emissions were 0.08 $gCH_4/h/m^2$. A decreasing trend was observed in both tanks along the longitudinal axis, indicating that dissolved $CH_4$ at the WRRF inlet, produced in the pre-denitrification tanks, is released into the atmosphere mainly in the initial part of the oxidation tank due to stripping induced by aeration. Considering the GWPs of $N_2O$ and $CH_4$, the average total emissions in $CO_2$ equivalent were about 20,000 $kgCO_{2eq}/d$ (96% due to $CO_2$ and only 4% due to $N_2O$ and $CH_4$). Indirect GHG emissions are related to the energy consumption of the blowers in the aerated tanks. In 2019, blower energy consumption was 9430 kWh/d. Considering a $CO_2$ emission factor for electricity production of 0.316 $kgCO_2/kWh$ [14], the indirect emissions of $CO_2$ were 2980 $kgCO_{2eq}/d$, i.e., about 1/6 of direct emissions.

The sampling carried out during the stationary tests showed that the trend of incoming pollutant loads, mostly of industrial origin, varies daily, weekly and seasonally with tannery activity. The inlet load increases on working days and gradually decreases over the weekend. The air flow supplied to the tanks follows the trend of the industrial wastewater entering the Cuoiodepur WRRF: the greater the load, the greater the air flow supplied. As the air flow increases, the OTE decreases. The trend of $CO_2$ emissions follows that of inlet COD, and therefore that of the organic load entering the tank. $N_2O$ emissions are mainly influenced by DO and air flow. When the DO concentrations dropped sharply, presumably due to an increase in biological activity caused by an increase in input load (followed by higher air flow supplied to restore the DO set-point), emissions increased (14-18 $ppmN_2O$). This is in line with the literature: sudden changes in process conditions can determine an increase in $N_2O$ emissions [15]. $N_2O$ production under limiting oxygen conditions (< 1 mg DO/l) in the oxidation tanks is due to denitrification by ammonium-oxidizing bacteria [16]. Moreover, as the air flow increases, stripping increases and therefore also $N_2O$ emissions from the oxidation tank.

Regarding VOC and odour measurements at the East Rome WRRF, only 26 of the 130 VOCs analyzed (halogen-derived compounds, nitrogen compounds, aliphatic and aromatic hydrocarbons, oxygenated compounds) in the oxidation tank were detected. In any case, all values were very low, and the VOCs detected are ubiquitous in outdoor places. The compounds detected in the highest concentrations were toluene (256 $\mu g/m^3$), m+p-xylene (28 $\mu g/m^3$) and o-xylene (12 $\mu g/m^3$). The average concentration of total VOCs was about 480 $\mu g/m^3$, which is a level in air acceptable for human health [17]. The average concentration of $H_2S$ was 0.17 ppm and the average odour unit was 5 $ouE/m^3$, which is also very low.

The LESSWATT protocol for WRRF carbon footprint reduction was applied to the Cuoiodepur WRRF. The biokinetic and hydrodynamic models were properly calibrated and validated in order to simulate plant operation and analyze different operational scenarios. The CFD-biokinetic integrated model was used to simulate different operational scenarios by varying parameters like air and influent flow rates. This demonstrated the effect of the different control strategies (based on DO, ammonium or SRT), dry or wet weather conditions and replacement of the air diffusers. Four scenarios were selected, three of which had different influent wastewater flow rates and a constant air flow rate, while in the fourth scenario a reduction in aeration was simulated as a mitigation strategy to minimize the carbon footprint. The results were compared in terms of changes in biological tank hydrodynamics and treatment performance in terms of COD and nitrogen removal. The scenario based on the aeration control strategy showed potential for reducing carbon footprint without compromising treatment performance. $N_2O$ risk assessment modeling made it possible to assess $N_2O$ production dynamics in the oxidation tanks of the WRRF.

## 4. Conclusions

Optimization of WRRF oxidation processes offers a concrete possibility for reducing plant energy consumption and carbon footprint. Aeration systems are responsible for 50-60% of total consumption and optimization of their management can have environmental and economic benefits. According to our experimental results, the LESSDRONE prototype, which was designed and built to monitor oxygen transfer efficiency and direct emissions from oxidation compartments, together with the LESSWATT protocol, are useful for carbon footprint assessment and minimization of WRRF oxidation processes. LESSDRONE also makes it possible to collect off-gas samples for analysis of VOCs and odour. The instrument is easy to maneuver, and thanks to its high degree of automation, and reduces the need for personnel to obtain measurements. The ability of the drone to move autonomously in aerated tanks with all the necessary instrumentation for measurements on board, ensures complete automatic mapping of the tanks. This is made possible by the movement and positioning systems (propeller motors and GPS) and batteries with one day autonomy mounted on the hood. For stationary measurements the instrument can be powered by an electric cable. The measurements obtained made it possible to fine-tune and optimize the testing procedures and the hardware and software of the prototype. The data acquired was consistent with the process conditions of the plant and offered new insights. The LESSDRONE output values proved to be reliable, repeatable and accurate. The tool makes it possible to adjust process conditions (air flow, DO, SRT) to reduce overall GHG emissions, whether direct emissions from the oxidation tanks or indirect emissions related to energy consumption. The experimental results and WRRF characteristics make it possible to determine optimal air flow and DO for pollutant removal and for minimization of the aeration carbon footprint and of emissions of VOCs and odour. When the air to be supplied decreases, the aeration system benefits as the oxygen transfer efficiency increases. By monitoring αSOTE, it was possible to optimize the methods and frequency of cleaning and/or replacing the air diffusers. The functionality and versatility of the drone are crucial for ensuring its transferability to other WRRFs that work in different operating contexts. Testing of the prototype in another five European WRRFs (3 Italian and 2 Dutch) with different inlet characteristics, plant layout and management technologies, has enabled a protocol applicable to a wide range of technologies and operating conditions. As we continue measurement campaigns in selected WRRFs, further data and information will be acquired towards development of the final protocol.

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