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Towards Energy Efficient Onsite Wastewater Treatment

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Abstract

The objective of this work is to demonstrate that some weaknesses of the onsite packaged WWTP associated with high operational costs and energy inefficiency could be overcome by improved management. The research methodology consists of series of batch studies with sludge from municipal or onsite WWTP, which simulate different working regimes of the onsite WWTPs – daily operation, toilet flushing and dishwasher machine. A simple classical tool, Oxygen Uptake Rate (OUR) is used to prove the hypothesis that regardless the specificity of the onsite WWTPs, namely the irregularity of the flow and load, three parameters follow similar increasing and decreasing trends – inflow rate, inflow pollution load and oxygen demand in the reactor. The literature review has not shown research publication about applicability of (OUR) for management of onsite WWTPs, but has shown experience and knowledge with municipal WWTPs, which were utilized in our study. The results prove that when there is no wastewater generation in the household, the (OUR) in the reactor is very low, 0.0007 to 0.0015 mg/l.s, thus do not require high oxygen supply. However, when wastewater flushes into the onsite WWTP, the oxygen demand increases rapidly and (OUR) reaches the range of 0.0040 to 0.0063 mg/l.s depending on the type and the quantity of the incoming substrate (pollution load). These results, if verified in filed experiments will enable optimization of the energy use during onsite WWTP operation. The suggestion is that the oxygen supply in the reactor should be adjusted according to the demand, respectively proportional to the inflow rate. In addition to the benefit of saving energy, the comprehensive sensors for dissolved oxygen monitoring, which require qualified maintenance could be avoided and replaced by simple sensors for level, which are anyway part of the equipment of most of the onsite packaged WWTP.

Keywords: Decentralized Wastewater Management; Individual or Other Appropriate Systems (IAS); Onsite Wastewater Treatment; Oxygen Uptake Rate (OUR); Energy Efficiency.

1. Introduction

The use of centralized systems in which wastewater is conveyed through a collecting system to a centralized Wastewater Treatment Plant (WWTP) is a general practice in urban wastewater management. However, a series of disadvantages, especially financial and ones in management arise from the application of these systems in rural and suburban areas, which are smaller in scale and have lower population density. The European Council Directive 91/271/EEC [1] stipulates that "*where the establishment of a collecting system is not justified either because it would produce no environmental benefit or because it would involve excessive cost, individual systems or other appropriate systems (IAS) which achieve the same level of environmental protection shall be used*". Among the various individual (on-site) solutions, one of the best options in terms of risks to health and environment, technologies and methods of

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operation and socio-cultural acceptance (not so much in terms of economic and financial issues), are the so called packaged or onsite wastewater treatment plants. These systems are designed as real treatment plants, but on a smaller scale. Provided that best practices for operation and maintenance are followed, they are a potential solution to wastewater treatment and in some cases, also to nutrient management [2]. They have been attracting more attention, especially in the growing cities where in the outskirt plots are much smaller than in rural areas. Thus IAS in suburb urban areas require more intensive treatment processes than classical IAS like septic tank plus soil infiltration systems [3]. However, all studies recognize that today, in the field of on-site WWTP, practical experience is still insufficient and that it is still necessary to develop effective management tools, especially in the long term.

Moelants et al. [4] studied twenty-three individual wastewater treatment systems installed in Belgium and conclude that 52% of these did not meet the quality standards required by legislation. This negative result was driven by shortcomings in the design, operation problems and inadequate maintenance interventions. The same authors have shown that, provided that there is frequent monitoring and maintenance, the quality prescribed by standard can be achieved [5]. Another observation of a bad performance of this type of IAS is made by Dubois et al. [3] who compared the design criteria of 141 onsite wastewater treatment systems in French market (attached and suspended growth systems). They conclude that all activated sludge systems are oversized, which results in high energy consumption, risk of nutrient deficiencies and development of filamentous bacteria. Similar is the discussion in the thesis of Furrer [6], who states that "*on-site wastewater treatment plants (WWTP) suffer from bad reputation due to their high failure rate. However, the poor performance is by a great deal caused by the insufficient monitoring and maintenance system*". Further, the study of Schneider et al. [7] demonstrates that sensors are actually the bottleneck of the on-site wastewater treatment systems, since their maintenance is time-consuming. The authors suggest management with soft sensors based on engineered features. Their study, however, shows that unmaintained sensors for dissolved oxygen are not reliable.

Despite the high variety of packaged WWTPs on the market, most of them use aerobic biodegradation processes, in which air blowers supply the required oxygen using energy. Depending on the producer, the working mode of air blowers might be different in level of complexity – simple, based on time switch, or more complicated automation based on sensors for the dissolved oxygen in the bioreactor [8]. The first working mode results in high energy consumption since equal oxygen is provided irrespective of the pollution load, i.e. real oxygen demand. The second mode requires qualified maintenance of the sophisticated sensor, which means higher operational costs.

Our study aims to demonstrate that some weaknesses of the onsite packaged WWTP associated with high operational costs and energy inefficiency, which were briefly discussed above, could be overcome by improved management. A simple classical tool, Oxygen Uptake Rate (OUR) was used in this research to prove the hypothesis that regardless the specificity of the onsite WWTPs, namely the irregularity of the flow and load, three parameters follow similar increasing and decreasing trends – inflow rate, inflow pollution load and oxygen demand in the reactor. The Oxygen Uptake Rate (OUR) measures the amount of oxygen that microorganisms consume in the unit of time [9], i.e. it measures indirectly a metabolic activity of the microorganisms. The higher the (OUR) is, the higher the metabolic activity is [10]. We assume that filed experiments will further verify that an operation mode of the blowers, adjusted in dependence on the level (i.e. incoming flow) will be possible. Respectively, we suggest oxygen supply to increase when water level increases and in the rest of the time the oxygen to be maintained at lower concentration. Such management will avoid the use of costly sensors for dissolved oxygen and will result in more efficient energy consumption.

The literature review has not shown research publication about applicability of (OUR) for management of onsite WWTPs, but has shown experience and knowledge with municipal WWTPs. Similar to our idea for use of (OUR) as a tool for energy optimization of IAS was reported by Kim et al. [11] for a municipal WWTP. Their results proved that measuring (OUR) together with DO and ammonium nitrogen enables more effective operation due to significant energy savings from less supplied oxygen. Something more, they conclude that all WWTPs with activated sludge process should consider (OUR) as an essential parameter in control strategies. Furthermore, a number of studies shows that a correlation between (OUR) and incoming pollution, as well as between (OUR) and final effluent quality exists, as stated by Wastewater Treatment Plant Operator Certification Training in 2014 [12]. Baeza et al. [13] have shown that the use of (OUR) measurements, connected to a mathematical model (ANN), allows management and improvement of biological processes in WWTPs. Pabitra [14] used (OUR) to determine the toxicity of different pharmaceuticals to the process of activated sludge treatment of municipal WWTPs. Another field of application are industrial aerobic biodegradation processes, where (OUR) is used for process optimization [15-17].

The knowledge, gained in municipal WWTP management and operation, was applied in this study to demonstrate the applicability of the (OUR) as a tool enabling improved management of the onsite WWTPs. The methods (experiment set up, determination of the (OUR), activated sludge used and experimental procedures) are presented in Section 2. The results and discussion are described in Section 3 and 4, respectively, followed by conclusions in Section 5

2. Methods

2.1. The Experiment Set Up

A laboratory scale bioreactor was used to simulate onsite WWTP. Air was supplied to microorganisms by aeration pump (ASF Thomas, Wisa Wuppertal). An electric stirrer (Heidolph, model RZR 2021) was installed to prevent sedimentation processes and microorganism deposits on the bottom, as well as to provide ease of mixing of sludge and substrate (as shown in Figure 1).

Figure 1. Reactor and equipment

2.2. Determination of the (OUR)

Calculation of (OUR) consists of determining the concentration of Dissolved Oxygen (DO) in activated sludge sample through an oximeter. Since the sample is not aerated during these measurements, oxygen concentration decreases over time generally according to a linear trend [18, 19]. By reporting the values of DO as a function of time and making a linear interpolation in a graph, it is possible to obtain (OUR) as a slope of the line interpolating the data (Figure 2).

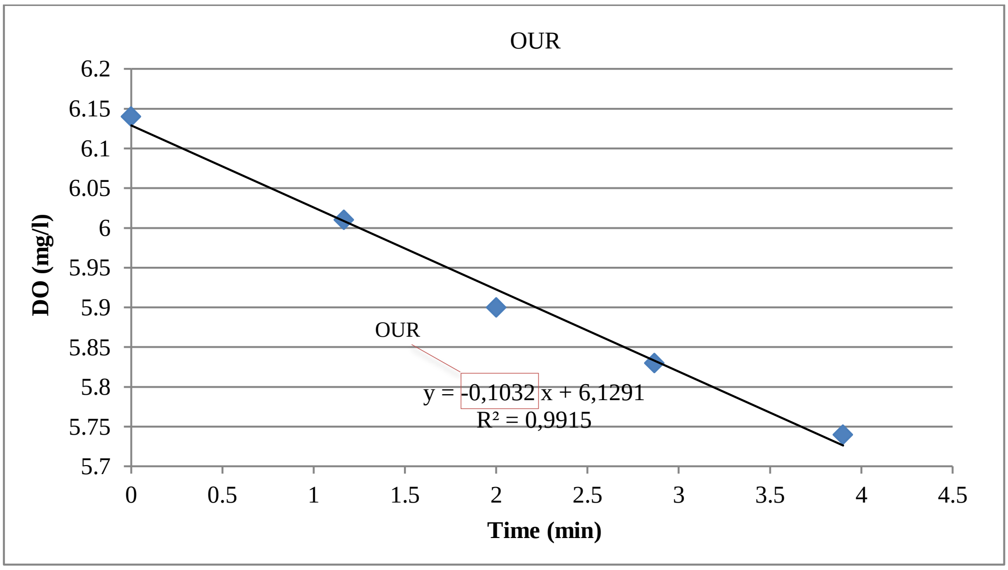

Figure 2. Example of (OUR) calculation as slope of the line interpolating DO data

(OUR) represents the rate at which microorganisms consume oxygen, which varies proportionally to the pollutant load and the rate of microbial growth. Therefore, following the increase in concentration of organic substance there is an increase in the consumption of oxygen by microorganisms that is required to degrade the substrate.

In the current studies, (OUR) was established by five DO measurements at an interval of about one minute. These measurements were performed once every hour, unless the substrate was added, in which case the measurements were taken with an interval of 10 minutes.

Considering that the amount of oxygen that microorganisms consume is proportional to the amount of substrate that is degraded in the unit of time, during the experiments, different substrate (in quantity and quality) was added to the bioreactor to simulate and test different working regimes of the packaged WWTP.

2.3. The Activated Sludge

Two types of activated sludge were used – from a private packaged WWTP and from a municipal WWTP and respectively, two types of studies were performed:

Study A: A mixture of wastewater and sludge was taken from a private house using a package WWTP system with activated sludge treatment.

Studies B and C: A mixture of wastewater and sludge was sampled from the bioreactor of Dupnitsa WWTP, Bulgaria, a municipal plant for about 82K p.e. The treatment technology of the WWTP consists of screening, grit-oil removal, and primary sedimentation, biological treatment in an activated sludge reactor without nitrogen and phosphorus removal and secondary sedimentation. On the sludge line there is anaerobic digestion and dehydration.

2.4. Experimental Procedures

The experimental procedures are visualized in Figure 3.

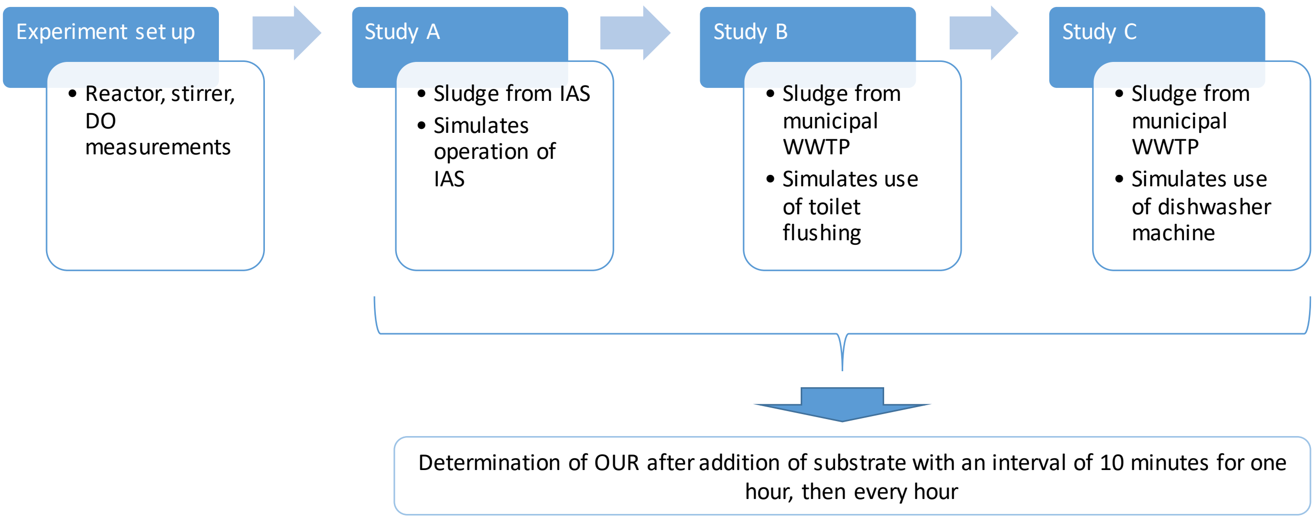

Figure 3. Flowchart of the experimental procedures

Study A: On-site WWTP sludge test

This study simulates the operation of an onsite WWTP. Even when there is no use of wastewater in the household, the recirculating system of the plant works and periodically pumps some wastewater from the effluent back to the inlet of the WWTP. This contribution corresponds to about 100-200 *ml* in a reactor of 2 *l*.

The experiment, lasting a total of 3 days, was divided into three trials, each trial lasted approximately 24 hours. The procedures are shown in Table 1:

Table 1. Procedures of study A

	Initial Volume	(OUR) Measurement	Addition of Substrate	(OUR) Measurement
Trial 1	2.1 *l* activated sludge	one control measurement	100 *ml* of wastewater	with an interval of 10 minutes for one hour, then every hour
Trial 2	2 *l* activated sludge	one control measurement	200 *ml* of wastewater	with an interval of 10 minutes for one hour, then every hour
Trial 3	The Same as Trial 2			

Study B: Municipal WWTP sludge test

This study simulates use of toilet flushing in a household. This contribution of about 10 *l* flushings water in a reactor with 1 m^3 of volume, corresponds to about 20 *ml* in a volume of 2 *l*. The procedure followed is shown in Table 2:

Table 2. Procedures of study B

	Initial Volume	OUR Measurement	Addition of Substrate	OUR Measurement	Addition of Substrate	OUR Measurement
		9:00 am to 11:00 am	at 11:00 am	11:00 am to 3:00 pm	at 3:00 pm	3:00 pm to 5:00 pm
Trials 1 and 2	2 *l* activated sludge	control measurement once an hour	20 ml of wastewater	with an interval of 10 minutes for one hour, then every hour	20 *ml* of wastewater	with an interval of 10 minutes for one hour, then every hour

Study C: Municipal WWTP sludge test plus detergent

The study simulates the use of dishwasher machine in a household. Biodegradable dishwashing detergent diluted with tap water in corresponding concentration was used. In order not to exhaust the sludge, the tests with detergent were made with an interval of more than 24 h.

Table 3. Procedures of study C

	Initial Volume	(OUR) Measurement	Addition of Substrate	(OUR) Measurement	Addition of Substrate	(OUR) Measurement
		9:00 am to 11:00 am	at 11:00 am	11:00 am to 3:00 pm	at 3:00 pm	3:00 pm to 5:00 pm
Trial 1	2 *l* activated sludge	control measurement once an hour	20 *ml* of wastewater plus 30 *ml* of detergent diluted in tap water	with an interval of 10 minutes for one hour, then every hour	20 *ml* of wastewater	with an interval of 10 minutes for one hour, then every hour
Trial 2	2 *l* activated sludge	control measurement once an hour	20 *ml* of wastewater	with an interval of 10 minutes for one hour, then every hour	20 *ml* of wastewater plus 30 *ml* of detergent diluted in tap water	with an interval of 10 minutes for one hour, then every hour
Trial 3	2 *l* activated sludge	control measurement once an hour	20 *ml* of wastewater	with an interval of 10 minutes for one hour, then every hour	20 *ml* of wastewater	with an interval of 10 minutes for one hour, then every hour

3. Results

Study A: On-site WWTP sludge test

The calculated (OUR) values for each measurement were plotted in graphs to demonstrate the dynamic of the (OUR) during the entire duration of the experiment (Figure 4).

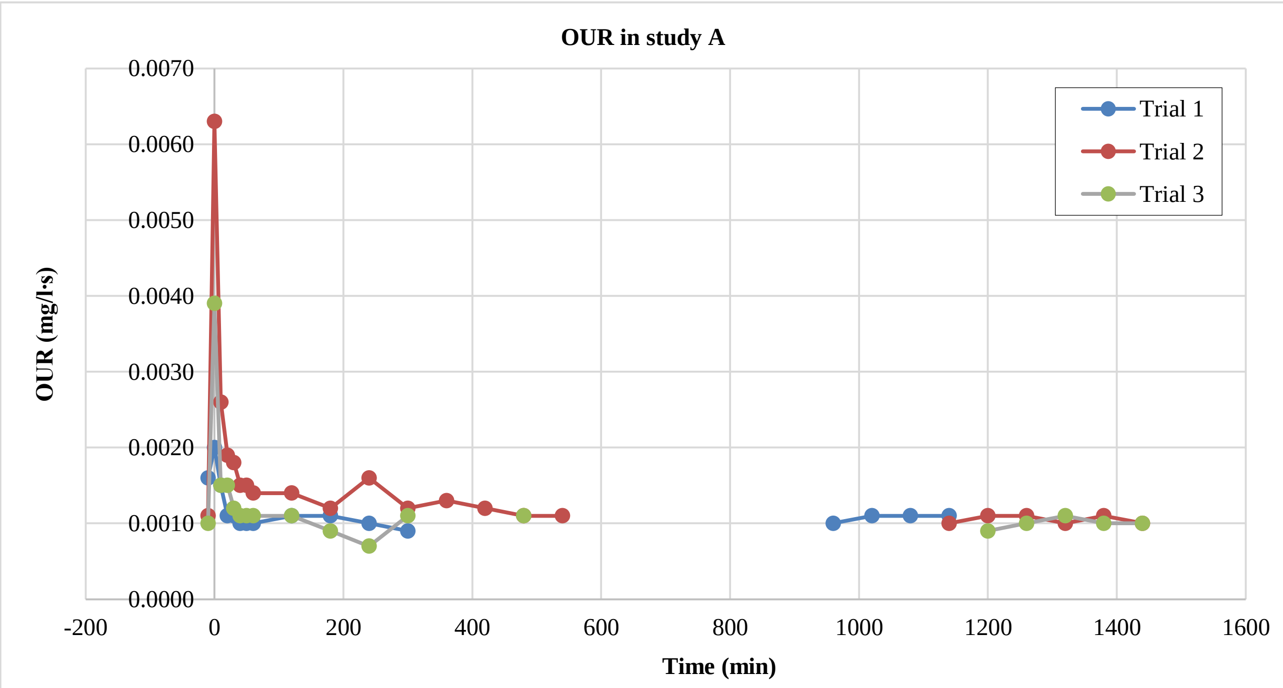

Figure 4. (OUR) results in study A

All three trials show similar trends. The initial (OUR) (before the addition of substrate) in the three trials are very close: 0.0016 mg/l·s; 0.0011 mg/l·s; 0.0010 mg/l·s. After the addition of the substrate, (OUR) significantly increases (time zero in Figure 4). After the initial increase of the (OUR), a quick decrease is detected. Ten minutes after the addition of the substrate, (OUR) decreased nearly twice in value. 20 minutes after the addition of the substrate, (OUR) returns back to nearly the same value before the addition of the substrate. After the first hour till the end of the experiment (after approximately 24 hours), (OUR) varies around its initial value.

Study B: Municipal WWTP sludge test

In the following graph the results of (OUR) are plotted against the time:

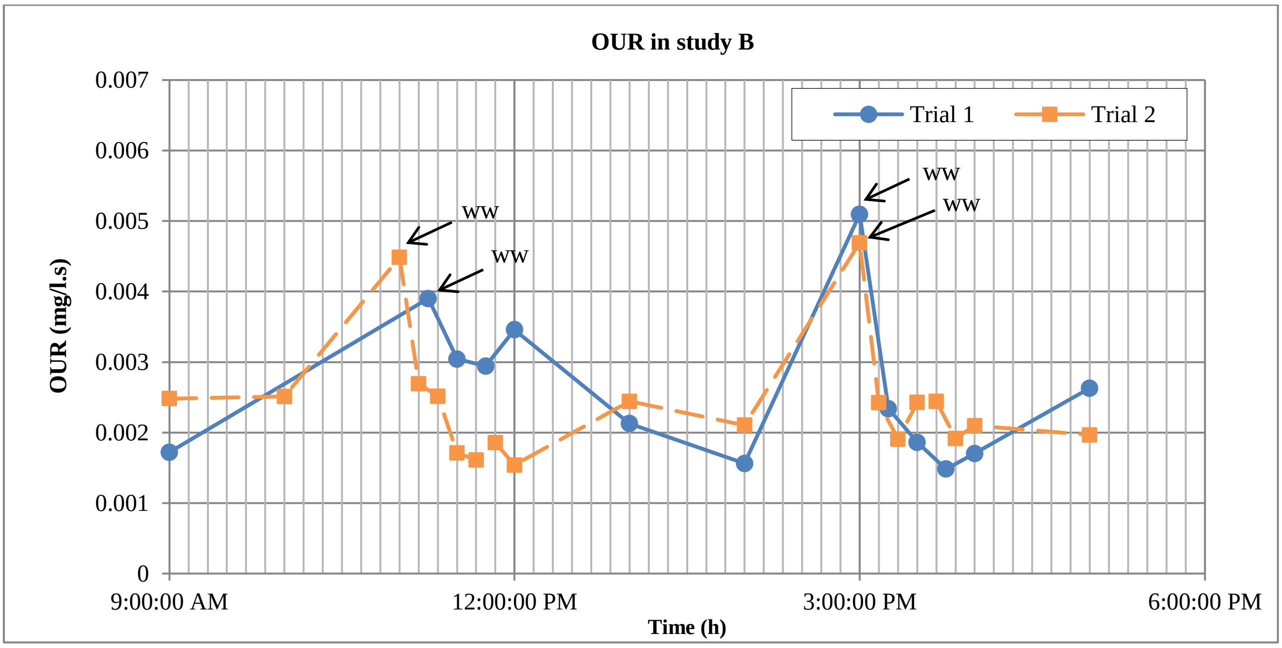

Figure 5. (OUR) results in study B (WW- wastewater)

Figure 5 shows that, as a result of the addition of the substrate, a peak always occurs, after which the values decrease and stabilize around an average value.

In the first trial the initial value of (OUR) is 0.0017 mg/l·s, but after the addition of substrate the values increase up to 0.004 mg/l·s, after which, about 10 min later, the results oscillate around the initial values. A further addition of substrate leads to an (OUR) of 0.0051 mg/l·s and after about 15 min values seem to stabilize. In the following trial there is a first peak of 0.0045 mg/l·s and a second peak of 0.0047 mg/l·s.

Study C: Municipal WWTP sludge test plus detergent

The results of this study are shown in Figure 6.

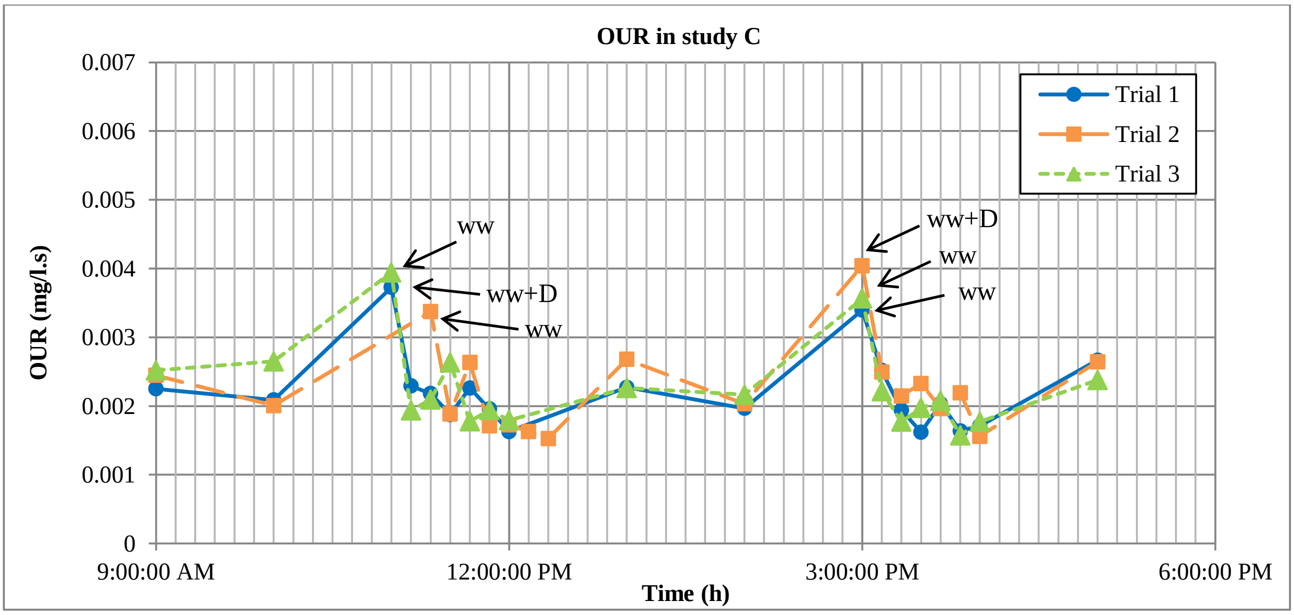

Figure 6. (OUR) results in study C (WW- wastewater; D - detergent)

Results show a trend in (OUR) similar to previous study, with an initial values of about 0.0025 mg/l·s and a peak after the substrate addition, respectively of 0.0035-0.0040 mg/l·s. In this case the values seem to stabilize around the initial value after about ten minutes from the load.

It can be noted, however, that in general the peak of (OUR) following the addition of detergent is higher than that following the addition of wastewater only. This confirms that (OUR) reflects the behavior of microorganisms in response to an organic load.

4. Discussion

In all cases (OUR) describes correctly the behavior of microorganisms. There is always a peak after the addition of substrate, which is due to the fact that when microorganisms receive "food" they are consuming a greater quantity of oxygen.

Food for microorganisms always arrives with the flow. In the cases, studied in our research, this was either toilet flush, dish washing machine outflow or internal recirculation in the bioreactor (due to the specificity of the studied onsite WWTP). Therefore, the supplied air could be controlled by a sensor for the incoming flow – more oxygen should be supplied when there is incoming flow (respectively food for the microorganisms) and correspondingly, less oxygen should be supplied when there are no household activities. Such working mode of the air blower will save energy and will reduce operational costs of onsite WWTPs.

Table 4 shows the maximum and minimum values of (OUR) measured in the different tests and the average values (calculated excluding the peak values).

Table 4. (OUR) in values in the three studies

(OUR) (mg/l·s)									
Trial	**Study A**			**Study B**			**Study C**		
	min	max	avg	min	max	avg	min	max	avg
1	0.0009	0.0020	0.0012	0.0015	0.0051	0.0023	0.0016	0.0037	0.0021
2	0.0010	0.0063	0.0016	0.0015	0.0047	0.0022	0.0015	0.0040	0.0021
3	0.0007	0.0039	0.0012	-	-	-	0.0016	0.0039	0.0021
All trials	**0.0007**	**0.0063**	**0.0013**	**0.0015**	**0.0051**	**0.0023**	**0.0015**	**0.0040**	**0.0021**

The comparison of the three studies shows lower average and minimum values in the study with sludge from the onsite WWTP.

The literature review did not show a study for (OUR) with activated sludge from on-site WWTP. To verify the obtained values, studies with activated sludge from municipal WWTPs were used (Table 5):

Table 5. (OUR) defined in other studies

(OUR) (mg/l·s)	Experiment characteristics	Reference
0.003	Activated sludge and substrate from municipal WWTP	[20]
0.002	15°C, activated sludge from municipal WWTP, experiment with 1 liter volume	[21]
0.0036	20°C,activated sludge from municipal WWTP, experiment with 1 liter volume	[21]
0.0052	25°C, activated sludge from municipal WWTP, experiment with 1 liter volume	[21]
0.0088	30°C, activated sludge from municipal WWTP, experiment with 1 liter volume	[21]
0.0022	1 *l* sludge from municipal WWTP in Italy, addition of 10 mg/l of COD equivalent of sodium acetate	[22]
0.0061 to 0.001	Activated sludge and substrate from municipal WWTP	[23]

The Chalsani et al. [21] results prove the relationship between (OUR) and temperature: an increase in temperature leads to an increase in microbial activity, i.e. an increase in microbial respiration rate. Considering that, study A was conducted in October and studies B and C in January at heated room temperature, the reference results for temperatures of 15 °C and 20 °C of Chalsani et al. [21] are more suitable for a comparison.

The average value of (OUR) in the experiment A is 0.0013 mg/l·s (Table 4), is slightly less than the value of Chalasani et al. [21] obtained at 15 °C, but approximately three times lower than what he obtained at 20 °C. The reason for this difference seems obvious: in the municipal WWTP microorganisms receive "food" almost constantly, while in onsite WWTP it is at long time intervals (depending how active the owners are). Therefore, it is logical (OUR) in onsite WWTP to be lower.

In study B the average value of (OUR) is 0.0023 mg/l·s, whereas in study C it is 0.0021 mg/l·s (Table 4), in accordance with the value obtained from Chalsani et al. [21] at 15 °C. The study of Arias-Navarro et al. [23] clearly shows that depending on the sludge state (fresh or in endogenous phase) the (OUR) varies in wide range. Their results with the sludge in endogenous phase are close to the values, obtained in our study in which the sludge is also in endogenous phase due to limited "food" received.

Also the results of Ziad et al. [20] and Torretta et al. [22], respectively of 0.003 and 0.0022 mg/l·s (Table 4), are in agreement with the results of study B and study C, while a lower average value is found in the study A. In this case the difference could be due to the smaller amount of food provided to the microorganisms in single households. As aforementioned, households have certain patterns of irregular wastewater generation (simulated in the experiments), while the more houses are connected to a sewer the more regular the food provision to the microorganisms is.

However, it should be noted that the (OUR) depends on the concentration of the microorganisms in the reactor, that is why the values of (OUR) between different experiments should be considered only in regard to the trend they represent.

5. Conclusion

Onsite WWTPs are environmentally sound solutions for isolated houses. However, '*at present, such systems hold an uncertain status and are frequently omitted from consideration*. *Their potential can only be realized with improved approaches to their management*.' [24].

The validity of respirometric tests as a tool for optimization, control and management of biological processes in wastewater treatment plants, has been confirmed for decades, but the applicability to on-site plants have not been well studied. The experiments, presented in this paper, reveal that (OUR) could be an appropriate management tool for on-site WWTPs, being an easily assessable parameter and being able to immediately provide results on the development of these processes.

The results of the laboratory experiments support the hypothesis for possible optimization of the energy use during onsite WWTP operation based on a simple sensor measuring the level of the wastewater. The study shows that when there is no wastewater generation, the (OUR) in the reactor is very low, 0.0007 to 0.0015 mg/l.s, thus do not require high oxygen supply. However, when wastewater flushes into the onsite WWTP (i.e. water level increases), the oxygen demand increases rapidly and (OUR) reaches the range of 0.0040 to 0.0063 mg/l.s depending on the type and the quantity of the incoming substrate. These results should be further verified with field experiments. More research is needed to deepen the understanding in various aspects – what is the daily, weekly and seasonal dynamic of (OUR); how do different detergents in the market affect (OUR); what happens after long absence of the owners of the house, etc. This knowledge will potentially help in designing a less-energy demanding onsite WWTPs as well as in their improved operation.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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