Water Science & Technology

Water Science & Technology Vol 85 No 4, 1090 doi: 10.2166/wst.2022.025

Prediction of household wastewater treatment systems' *in situ* performance based on standardized tests

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ABSTRACT

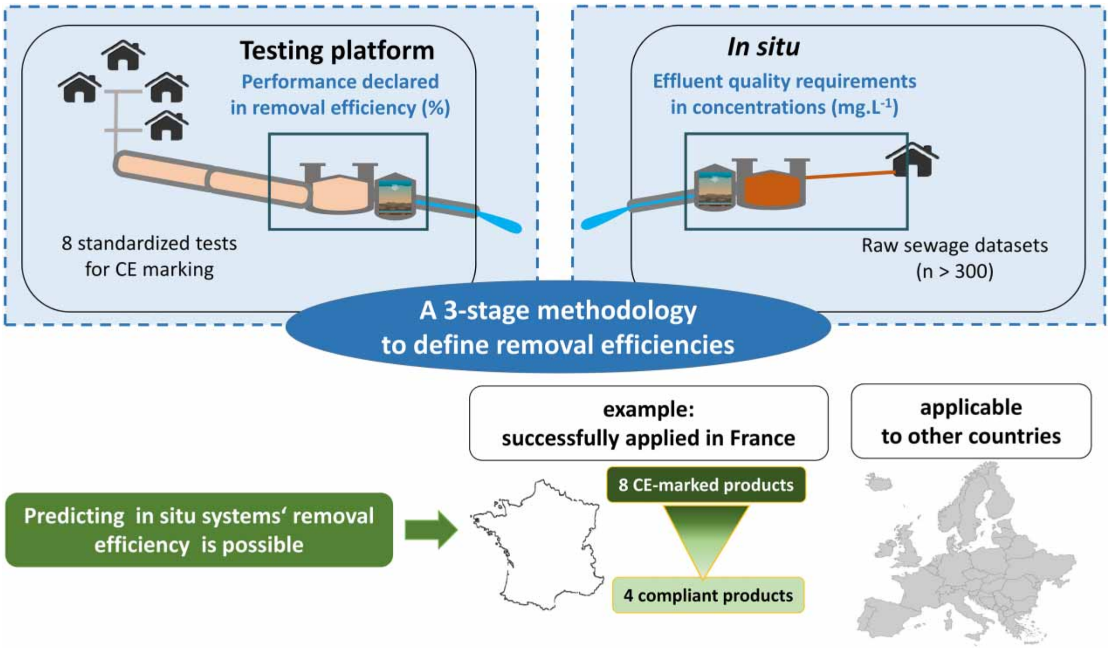
This paper presents a comparative analysis on operating conditions of onsite wastewater treatment systems. Actual EU Member States' national regulations require *in situ* treatment thresholds expressed in effluent concentrations. CE marking of onsite wastewater treatment system is mandatory according to standardized test (EN 12566-3 + A2) with performance declared in removal efficiency. Recent study indicates that *in situ* raw sewage concentrations are 1.5 times higher than those on test platforms. In this context, performance comparison between platform tests and *in situ* discharge threshold cannot be based on effluent concentrations but rather on removal efficiency to fulfill environmental and health requirements. This study compares: (i) results from eight standardized tests, (ii) over 300 measurements of *in situ* raw sewage, and (iii) several national-level thresholds focusing on carbon parameters. To meet French effluent thresholds, a minimum removal efficiency of 96% in SS and 95% in BOD_5 is required. A beta law model assesses the efficiency measured during standardized testing and establishes a robustness characteristic with a probability above 80%. When a septic tank is used, its efficiency can be incorporated into the prediction. Although the new performance criteria are more stringent, some of the eight products evaluated still meet the requirements.

Key words: carbon, domestic wastewater, EN 12566-3 + A2 Standard, modeling, onsite wastewater treatment, single-family dwelling

HIGHLIGHTS

- Platform-measured removal efficiency predicts compliance (or not) with regulatory requirements.
- Required removal efficiencies are specific to each parameter and exceed 89% in France.
- Modeling a portion of results evaluates the robustness of efficiencies measured on platform.
- *In situ* and platform raw sewage concentrations are different.
- Calculations include different septic tank removal efficiencies between *in situ* and platform.

GRAPHICAL ABSTRACT



INTRODUCTION

When a dwelling is not connected to a public sewer network, it must be equipped with an 'onsite wastewater treatment system' (OWTS) in order to treat the domestic wastewater it produces. In France, owing to the country's relatively low housing density, especially in rural areas, this type of onsite treatment system is extremely well developed with nearly 5 million total OWTS treating wastewater produced by 15% to 20% of the nation's population (Ayphassorho *et al.* 2014).

To preserve human health and the environment, these installations are subject to regulations. The CE marking, which enables the free trade of products within the European Union's single market, is mandatory for all products within the scope of the EN 12566-3 + A2 Standard (European Committee for Standardization 2013). This standard includes a test procedure to evaluate the treatment efficiency; this standardized test must be conducted by an independent third-party laboratory (one of the EU Member States' notified bodies). Based on the results obtained during this standardized test, the manufacturers must therefore declare the performance of their wastewater treatment products in terms of removal efficiency. There is no threshold value related to the declared performance.

Moreover, the European environmental regulatory framework requires for each Member State to adapt their national regulations to ensure compliance with purification performance benchmarks. In 2013, the 2nd CEN seminar on 'National requirements for small wastewater treatment plants <50 population equivalent (PE) in Europe' (Dierick *et al.* 2013) provided the then-current requirements in seven European countries: Austria, Belgium (Wallonia and Flanders), France, Germany, Ireland, Spain, and Sweden. For these eight countries and regions, the *in situ* treatment thresholds, expressed in maximum effluent concentrations, varied from 30 to 60 $mg{\cdot}L^{-1}$ SS, 90 to 150 $mg{\cdot}L^{-1}$ chemical oxygen demand (COD), and 20 to 40 $mg{\cdot}L^{-1}$ biochemical oxygen demand $(BOD)_5$. Requirements may simultaneously apply to all three carbon parameters, like in Spain, or only a couple of parameters (suspended solids (SS) and COD or COD and BOD_5). Some countries also add an effluent requirement pertaining to ammonia nitrogen. In France, the modified decree dated September 7, 2009 (Ministres d'Etat 2021) sets requirements as thresholds of 30 $mg{\cdot}L^{-1}$ SS and 35 $mg{\cdot}L^{-1}$ BOD_5. In this context, it appears difficult to determine if the declared performance of CE-marked products in terms of removal efficiency complies with the different member states' requirements expressed in maximum effluent concentrations.

Results from *in situ* monitoring in France, as conducted by Irstea in 2016 (Olivier *et al.* 2019a), have shown that, among the twenty types of approved-products studied, only four proved to be 'acceptable' in terms of wastewater treatment quality. This demonstrates a gap between product performance obtained during standardized tests on platform and taken into account by the French approval procedure, and the actual performance of onsite wastewater treatment serving individual dwellings in France. In Belgium, *in situ* performance assessment of CE-marked onsite individual wastewater treatment systems reveals that 52% of the 23 studied systems do not meet the legal effluent standards in Flanders and in Wallonia (Moelants *et al.* 2008). The highly variable *in situ* raw sewage (RS) quality and quantity from individual home is one of the possible explanations for such results. Similar observations have also been reported in the United States for onsite treatment systems certified under NSF-40 Class 1 (National Sanitation Foundation 2019). Based on *in situ* evaluation of onsite treatment systems over the years in Wisconsin, Converse (2004) indicated that compliance of treated effluent concentrations to certification threshold values (25 $mg{\cdot}L^{-1}$ SS and 30 $mg{\cdot}L^{-1}$ BOD_5) varied from 57 to 100% of the time for SS and from 49 to 99% of the time for BOD_5. Similarly, in Florida, compliance rates to the Class 1 threshold values are ensured only 78% of the time for BOD_5 and 64% of the time for SS (Ursin & Roeder 2013). All the cited *in situ* evaluation of onsite wastewater treatment performance indicate discrepancy between *in situ* results and those obtained during standardized test on platform. However, none of them compared the testing conditions on platform with *in situ* reality in terms of RS quality and quantity, as a potential explanation for this disparity.

Based on enhanced knowledge of *in situ* RS characteristics, which were not available when the EN 12566-3 + A2 Standard was issued, this paper aims to compare the *in situ* and platform approaches, as well as to identify the link between declarations of performance measured on platform, expressed either in terms of removal efficiency or in concentrations, and the *in situ* quality requirements target. The objective here is to confirm whether the standardized tests carried out on platform ensure meeting the required effluent quality in field conditions. The present work program focuses on the three carbon parameters used in different national regulations i.e. SS, COD and BOD_5. Analysis of nitrogen removal performance would require more technical elements not always easily accessible and some probably considered as part of the manufacturer's intellectual property.

The differences between platform and *in situ* conditions are introduced by means of comparing the characteristics of RS in terms of flows, concentrations and loads. Results from this comparison then allow the proposition of a methodology based on removal efficiency, in order to establish the closest possible correspondence between the two approaches and define the platform target best adapted to actual *in situ* considerations. As such, this analysis relies on data coming from eight tests conducted on four European test platforms, as well as data characterizing French household RS. The results reported, based on the French *in situ* situation, are expected to apply across Europe.

MATERIALS AND METHODS

Comparison of testing conditions on platform and *in situ* reality in terms of RS quality, quantity and load is performed using: (i) data available for both conditions, (ii) methods to calculate required *in situ* performance and (iii) by applying different statistical analysis.

Data available for platform test conditions

To reflect the platform testing conditions, the data analyzed in this study came from eight tests conducted on four European test platforms. Daily volumes and concentrations of the three carbon parameters (SS, COD and BOD_5) are considered, as well as the removal efficiency measured during these standardized tests for the same parameters.

The data measured on testing platforms have been derived from standardized test procedures according to the requirements listed in the harmonized EN 12566-3 + A2 Standard relevant to the CE marking. For this study, confidential results were available from eight products tested at four distinct European platforms named P1, P2, P3 and P4 in the text, including two in France. Those eight products belong to different wastewater treatment families, i.e. five are within the Attached Growth Systems on Fine Media (AGSFM) family, two within the Submerged Attached Growth Processes (SAGP) family, and the last one belongs to the Activated Sludge Processes (ASP) family (Olivier *et al.* 2019a).

The AGSFM family generally includes products comprising a septic tank and a filter. The filter process involves two mechanisms: (i) SS are mechanically filtered at the surface of the filtering medium, (ii) dissolved pollution is degraded by bacteria attached on the naturally aerated filtering medium composed of different materials ranging from: sand or other mineral materials, e.g. zeolite; organic materials, e.g. coconut fragments; or also synthetic materials. Reed bed filters are also included in this category. The acronyms AGSFM1 to AGSFM5 refer to the five studied systems belonging to this treatment family. Products of the type SAGP and ASP families contain a primary treatment system, a biological reactor and a clarifier. After physically separating a portion of the solid matter by means of sedimentation, the dissolved pollution is degraded by bacteria either attached on supports (SAGP family) or suspended in water (ASP family). The biological reactor operates in forced aeration mode. The sludge produced by biological treatment first sediment in the clarifier before being stored in the primary settling tank. The acronyms SAGP1 and SAGP2 refer to the two studied systems belonging to the Submerged Attached Growth Processes family, and the ASP1 acronym to the only system belonging to the Activated Sludge Processes family.

During the standardized tests conducted between 2006 and 2016, samples were drawn at both the system inlet and outlet, providing RS and treated wastewater datasets. The number of samples available (identical at inlet and outlet) is indicated in Table 1. The AGSFM3 product was sampled a second time within the framework of a protocol extending beyond what is required by the standard. For the ASP1 product, desludging occurred during the test and samples are thus divided into two sets, according to the desludging date. Table 1 also lists the number of data points in compliance with the RS concentration ranges mandated by EN 12566-3 + A2 Standard, either exclusively for the carbon parameters or for the entire set of parameters, including nutriments.

The nominal daily volume is fed on a platform according to a schedule simulating a household's typical lifestyle, with peaks in the morning and evening, plus two periods of zero contribution, in particular in the afternoon and at night. The exact chronology of the 24-hour scheme, expressed as a percentage of daily volume, is as follows: 3 hours at 10%, 3 hours at 5%, 6 hours at zero flow, 2 hours at 20%, and 3 hours at 5% before a second zero flow period of 7 hours. A complete test is composed of a series of ten sequences, eight of which include sampling. Among these eight sequences sampled, five correspond to the nominal input flow (of 150 $L \cdot d^{-1} \cdot PE^{-1}$), two to a lower load condition at 50% of the nominal input flow, and one to 150% overload conditions for two days (for nominal flows less than 1.2 $m^3 \cdot d^{-1}$). Other stresses are applied to the tested product during some sequences, like a 24-hour electricity outage and peak flows simulating bathtub draining. In all, 26 composite samples over 24 hours are taken at inlet and outlet. For three products (AGSFM1, AGSFM3 and AGSFM5), concentrations measured at the septic tank outlet are also available.

The removal efficiency of products tested on platform is determined based on 20 samples taken at nominal load (see Table 1) as declared by the manufacturer for CE marking. Results obtained for each product are provided in Table 2.

Data available for *in situ* conditions

The second part of the dataset, reflecting *in situ* conditions, comes from a RS evaluation study involving 15 French households (Olivier *et al.* 2019b; Dubois *et al.* in press). In addition, the hydraulic flow was continuously monitored for three of them. Overall, 302 samples characterizing RS were generated, along with three datasets of hourly volumes measured over a 20 to 26-month periods (Dubois, *publication forthcoming*).

Calculation of estimated efficiency for compliance with *in situ* regulatory requirements

The *in situ* efficiency target was estimated from effluent concentrations required, which vary from country to country, as well as from the 80th percentiles of *in situ*-measured RS concentrations distributions (Olivier *et al.* 2019b), in accordance with the following equation:

$$\eta_{estimated\ in\ situ} = \frac{\text{80th RS percentile} - \text{required effluent concentration}}{\text{80th RS percentile}} \qquad (1)$$

The 80th percentiles were used in order to satisfy the concentration criteria in 80% of situations encountered *in situ*. These estimated *in situ* efficiencies correspond to the minimum product's removal efficiency required during standardized tests so as to ensure compliance with regulatory requirements.

These required performances can be then refined for the various treatment families. For the AGSFM family, the platform removal efficiency can be adjusted if the septic tank platform efficiency as well as that of the filter are both known. More specifically, the overall efficiency of AGSFM-type products may be broken down as follows:

$$\eta = \eta_{septic\ tank} + \eta_{filter}\,(1 - \eta_{septic\ tank}) \qquad (2)$$

Based on the hypothesis that the filter removal efficiency is the same in both conditions, i.e. platform and *in situ*, and by taking into account the difference between septic tank efficiency in both conditions (see the 'Results and Discussion' section),

Table 1 | Number of samples available for the eight products studied

Platform			**P1**				**P2**	**P3**			**P4**
Product			**AGSFM1**	**AGSFM2**	**AGSFM3**	**AGSFM4**	**AGSFM5**	**ASP1a before desludging**	**ASP1b after desludging**	**SAGP1**	**SAGP2**
Number of samples	Total		26	26	26 (+11[a])	26	26	14	12	26	26
	At the nominal load		20	20	20 (+3[a])	20	20	12	8	20	20
	At the nominal load and in compliance with RS concentration mandated by EN 12566-3 + A2 for parameters:	SS, COD and BOD_5	14	19	19 (+3[a])	18	20	12	7	11	17
		all [b]	14	17	18 (+2[a])	18	11	12	7	10	15

[a]Additional samples.

[b]Parameters: SS, COD and BOD_5, NH_4^+-N, KN and TP.

Table 2 | Platform-measured removal efficiency for the eight products during tests conducted under nominal load conditions according to EN 12566-3 + A2 standard

Platform		P1				P2	P3		P4
Product		**AGSFM1**	**AGSFM2**	**AGSFM3**	**AGSFM4**	**AGSFM5**	**ASP1**	**SAGP1**	**SAGP2**
Removal (%)	SS	98.5	95.8	98.5	97.7	95.8	96.2	97.0	93.9
	COD	93.0	88.1	92.2	90.8	87.6	94.3	93.1	84.9
	BOD_5	98.5	96.2	98.2	97.2	95.0	98.1	97.1	94.3

it is possible to establish a correlation between platform efficiency and *in situ* efficiency, i.e.:

$$\eta_{estimated\ on\ platform} = \eta_{platform\ septic\ tank} + (1 - \eta_{platform\ septic\ tank}) * \frac{\eta_{estimated\ in\ situ} - \eta_{in\ situ\ septic\ tank}}{1 - \eta_{in\ situ\ septic\ tank}} \quad (3)$$

Taking conventional values of *in situ* septic tank removal efficiency from the literature (U.S. EPA 2002; Siegrist 2017) along with the septic tank removal efficiency measured on the platform, the platform removal efficiency target values can be calculated based on the estimated *in situ* values. The configuration of SAGP and ASP-type products generally does not allow any evaluation of secondary treatment efficiency, as is the case with the AGSFM family. Therefore, it is not possible to refine the analysis at this level and the *in situ* efficiency values estimated using the 80th percentiles of RS have been adopted as an estimation of the minimum required platform efficiency.

Statistical methods employed

Boxplots

The boxplot type of statistical presentation (Figure 1) enables visualizing a data distribution with various descriptive statistical parameters, namely: the median, the two quartiles Q1 and Q3, the interquartile deviation (ID) covering 50% of the data, and the fences calculated by the following formulae:

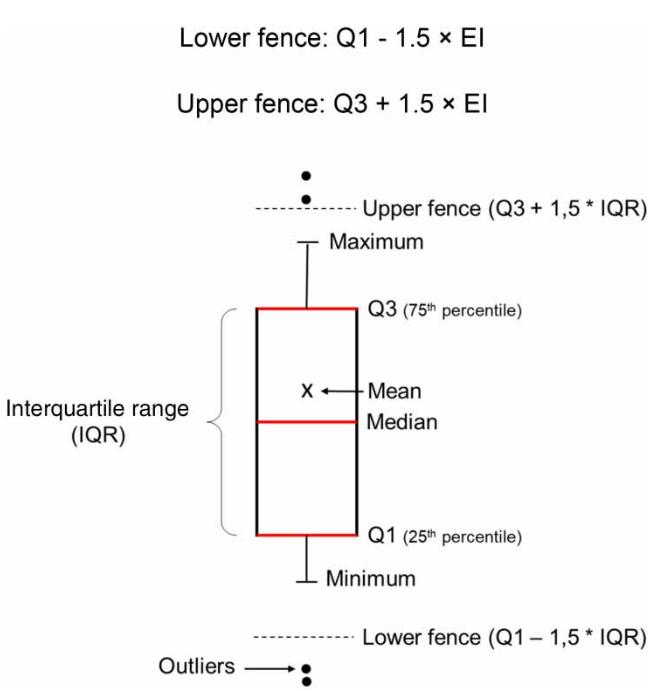


Figure 1 | 'Boxplot' type display of a data distribution.

In the case of a normal (or Gaussian) distribution, 99.3% of the data lie inside these two fences. The values exceeding the fences are thus qualified as 'outliers. This graphical representation enables comparing visually data distributions among themselves and deciphering trends. It does not however enable drawing a conclusion regarding statistically significant differences.

Kruskal–Wallis test and Wilcoxon–Mann–Whitney tests

To determine whether the samples stem from the same population or else multiple populations with identical characteristics, and when normal statistical distribution is not satisfied, then the Kruskal–Wallis test is used. This test entails a non-parametric variance analysis (ANOVA) evaluating the following null hypothesis:

H0: 'No difference exists between the samples.'

The test determines the probability p (p-value) of erroneously rejecting the null hypothesis H0. This hypothesis is not accepted if the p-value lies below the significance threshold α, typically set at 5%. If hypothesis H0 is rejected, it then becomes possible to perform multiple comparisons by relying on Wilcoxon–Mann–Whitney tests for the purpose of more accurately assessing which samples differ among one another. The outcome of these tests is indicated by letters in the boxplot figures representing the samples.

Linear regressions

Concentration measurements at the septic tank outlet conducted for products AGSFM1, AGSFM3 and AGSFM5 allow calculation of the surface loads applied to filters as well as the surface loads treated by these filters. Filter removal efficiency can thus be determined by linear regressions (i.e. filter removal efficiency equals the ratio between treated surface load and applied surface load). Moreover, these regressions lead to evaluating the removal efficiency stability via the analysis of the regression coefficient (Seber & Lee 2003).

Modeling platform-measured efficiency using the beta law

Platform-measured product efficiencies are studied to evaluate the robustness of results and hence product performance. With respect to data contained within a finite interval [0,1] and adhering to neither a normal law nor a log-normal law, data are modeled by means of the beta law. This law is characterized by two shape parameters, α and β (Forbes *et al.* 2010). Data are modeled with R software thanks to the fitdist() function. The pbeta(real, α, β) function is also used to calculate the probability that the law adopts a lower value than a given real number. It is thus possible to deduce the probability that a product complies with a particular efficiency threshold value. Figure 2 shows an example of modeling an efficiency distribution by a beta law. The graph on the left depicts both theoretical (in blue) and empirical probability densities, while the graph on the right is a 'Quantile–Quantile' diagram. These graphs enable visualizing the proper data adjustment to the derived model.

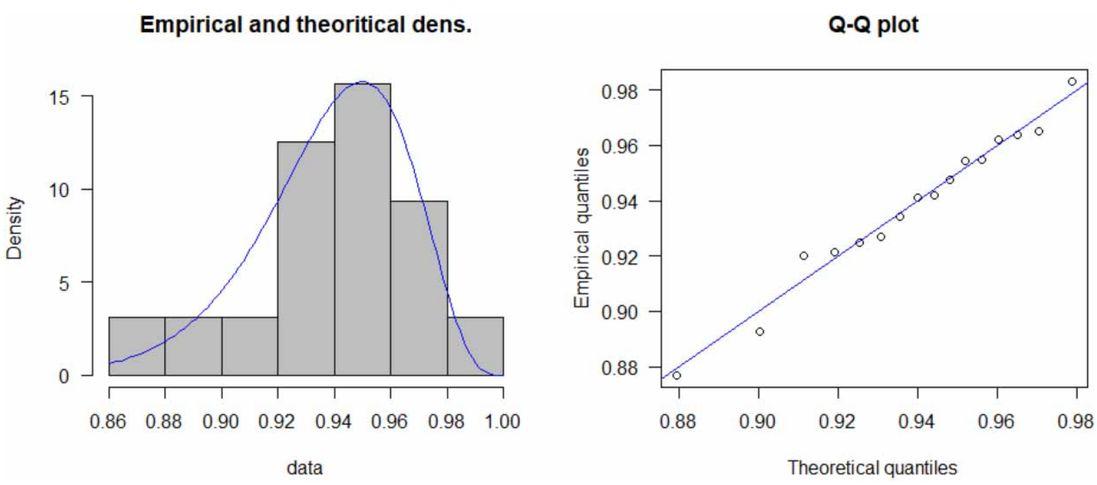


Figure 2 | Example of an efficiency distribution adjustment to a beta law.

For prediction based on beta law, only samples taken at nominal load conditions and respecting RS quality concentration limits stated by EN 12566-3 + A2 Standard are taken into consideration. Whenever one of the inlet concentration values lies outside of the range authorized in the standard, the entire set of concentrations characterizing the effluent is to be deleted (Table 1) to avoid bias in the analysis. Since the analysis is limited to SS, COD or BOD_5 parameters, RS non-compliance to nutrient parameters limits of the standard was not considered, thereby eliminating between zero and nine samples depending on the different platform datasets.

RESULTS AND DISCUSSION

Comparison of platform vs. *in situ* RS characteristics

The characteristics of platform and *in situ* RS to be treated by OWTS are compared in terms of concentrations, daily flows and daily organic loads.

Concentrations

The average SS, COD and BOD_5 concentrations of the RS from four European testing platforms are presented in Table 3; these values seem to be highly comparable, with for example average COD concentrations of 747, 729, 653 and 697 mg·L^{-1} for platforms P1, P2, P3 and P4, respectively. For each parameter, these distributions are visually compared using the boxplot type representations (Figure 3). The Kruskal–Wallis and Wilcoxon–Mann–Whitney tests are also conducted in order to identify the significant statistical differences between distributions (see the 'Materials and Methods' section).

These statistical tests have confirmed the trend in the visual analysis suggesting a non-significant difference between the SS concentration distributions of RS feeding the four platforms. In contrast, significant differences in COD and BOD_5 concentrations are identified: COD concentrations in the effluent feeding platform P1 are higher than those feeding platform P3; as for BOD_5, platform P2 stands out with higher concentrations than those of both P1 and P3. Despite the differences noted from a statistical standpoint for COD and BOD_5, deviations between average RS concentrations among the various test platforms do not exceed 14% for COD and 18% for BOD_5. Considering that the identified differences in terms of parameters come from different platforms, it is difficult to draw a general conclusion regarding RS quality differentiation from one platform to another. Hence, the RS concentrations from the four platforms are considered similar. Moreover, nearly all values (between 92 and 95% depending on the parameter) comply with the boundaries specified in EN 12566-3 + A2 Standard and listed in Table 3. Noticeably the SS concentrations lie within the lower range of this interval.

With the same methodology, the characteristic ratios used to qualify wastewater as 'domestic' are also compared among the four platforms. The average values of these ratios are presented in Table 3. It emphasizes that the COD/SS ratio does not differ statistically across platforms, although the COD/BOD_5 ratio of platform P1 is different and higher than that of the three other platforms. The COD/BOD_5 ratios strongly support the 'domestic' nature of the RS, in accordance with the so-called 'typical' interval provided by Henze *et al.* (2010): [2.0; 2.5].

Also, Table 3 clearly shows the difference in RS quality used on testing platforms with that observed *in situ*. The average *in situ* RS concentrations are consistently higher than the average concentrations on the four platforms, by factors of 1.48 for SS, 1.72 for COD and 1.58 for BOD_5. As the *in situ* RS is more concentrated (on average: 544 mg·L^{-1} SS, 1,212 mg·L^{-1} COD,

Table 3 | Average platform and *in situ* RS concentrations and typical 'domestic' wastewater ratios from the four testing platforms

		Average concentrations (mg·L^{-1})			Average ratios	
Measurement conditions		**SS**	**COD**	**BOD_5**	**COD/BOD_5**	**COD/SS**
Platform	P1	380	747	309	2.5	2.0
	P2	391	729	347	2.1	1.9
	P3	352	653	295	2.3	2.1
	P4	349	697	347	2.1	2.1
	Average of the 4 platforms	368	706	324		
	Range of EN 12566-3 + A2	200–700	300–1,000	150–500		
In situ (Olivier *et al.* 2019b)	Average	544	1,212	514		
	80th percentile	789	1,810	690		

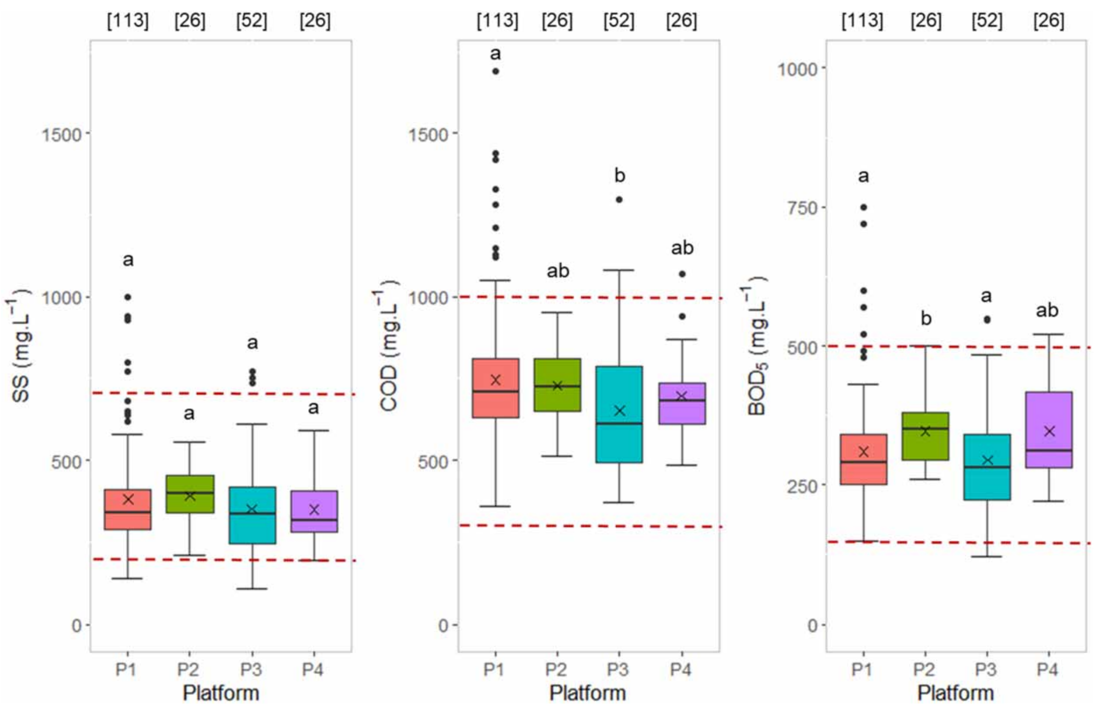


Figure 3 | Comparison of SS, COD and BOD_5 RS concentrations from four European testing platforms, with (shown in dashed lines) the minimum and maximum threshold concentrations allowed by EN 12566-3 + A2 Standard. Note: If two samples share the same letter (a or b), they are not significantly different, whereas if they display different letters, then the difference between them is deemed significant.

514 mg·L^{-1} BOD_5), effluent concentrations measured on platform cannot be used to check compliance with effluent concentrations required under *in situ* conditions. A simple comparison of these effluent concentrations between the two conditions, i.e. platform and *in situ* appears meaningless.

Flow rates

Standardized tests are conducted with a nominal daily flow rate of 150 L·d^{-1}·PE^{-1}, which corresponds to the 83rd percentile of the *in situ* daily flow rate per capita distribution. Under *in situ* conditions (Olivier *et al.* 2019a), the average daily volume discharged by a user is 98 L·d^{-1}, which is two-thirds of the standardized value. *In situ* flow rates are however extremely variable, with per-resident discharge volumes of 41 L·d^{-1} and 175 L·d^{-1} for the 10th and 90th percentiles, respectively. The hydraulic load for treating a single-family dwelling has been defined by these two boundaries (Dubois, *publication forthcoming*), therefore the average hydraulic load of a standardized test at 5 PE is compared to the 90th percentile of the distribution of *in situ* flow rate per standard household. The result corresponds to higher platform flow rate value, by a factor of 1.30 compared to *in situ* conditions (see Table 4).

Table 4 | Comparison of hydraulic and organic loads measured both on platform and *in situ*

Measurement conditions		Hydraulic load (L·d^{-1})	Organic load (g·d^{-1})		
			SS	COD	BOD_5
Platform: average loads for 5 PE	P1	733	261	518	216
	P2		273	505	241
	P3		247	460	207
	P4		237	478	239
	Average of the 4 platforms		254	490	226
In situ: 90th percentile of individual dwelling (Dubois *et al.* in press)		568	305	676	281

During a given day, incoming flows feeding an OWTS vary depending on the residents' uses. In this context, it is necessary to compare the hourly flow rates of both platform and *in situ* conditions in terms of hydraulic peak factor, which is defined as the ratio between the maximum hourly flow rate and the average hourly flow rate observed over the day. On the platform, two types of hydraulic peaks are generated according to the requirements of EN 12566-3 + A2 Standard. First, the feeding profile systematically includes a two-hour period during which 40% of the daily volume is applied on tested products (Figure 4), thus generating on each testing day a peak factor of 4.8, whose effects can indeed be measured. Next, during the test sequences carried out at nominal load, a particular higher peak[1] is simulated once a week, corresponding to a peak factor of 17.6. Despite their strong intensity, these peaks, whose occurrence dates are not systematically identified in the test reports, only impact the removal efficiency calculation when the sample is taken at just the right time to qualify the consequences of the particular peak on performance. Moreover, given the lack of sampling protocol details in the standard, the occurrence of this exceptional peak provides, up to now, no useful information on the product performance. From the *in situ* RS study, the three hourly volume datasets available (Olivier *et al.* 2019b) provide more than 1500 daily peak factor values, with an average of 7.9, which is a much higher value than the daily peak of 4.8 applied on testing platform. To increase the representativeness of standardized tests, a new daily flow distribution is proposed in Figure 4, resulting in a peak factor of 7.2 on each testing day. This modified distribution does not affect the overall shape of the flow distribution diagram currently in use, but solely modifies the peak flow, which becomes, for a 5-PE product, 225 L in one hour instead of 300 L in two hours.

Daily organic loads

In order to compare the pollution load on platform with most situations encountered *in situ*, the average organic loads measured during standardized tests on 5-PE products are compared with the 90th percentiles of the *in situ* distributions of RS organic loads from individual dwelling (Table 4).

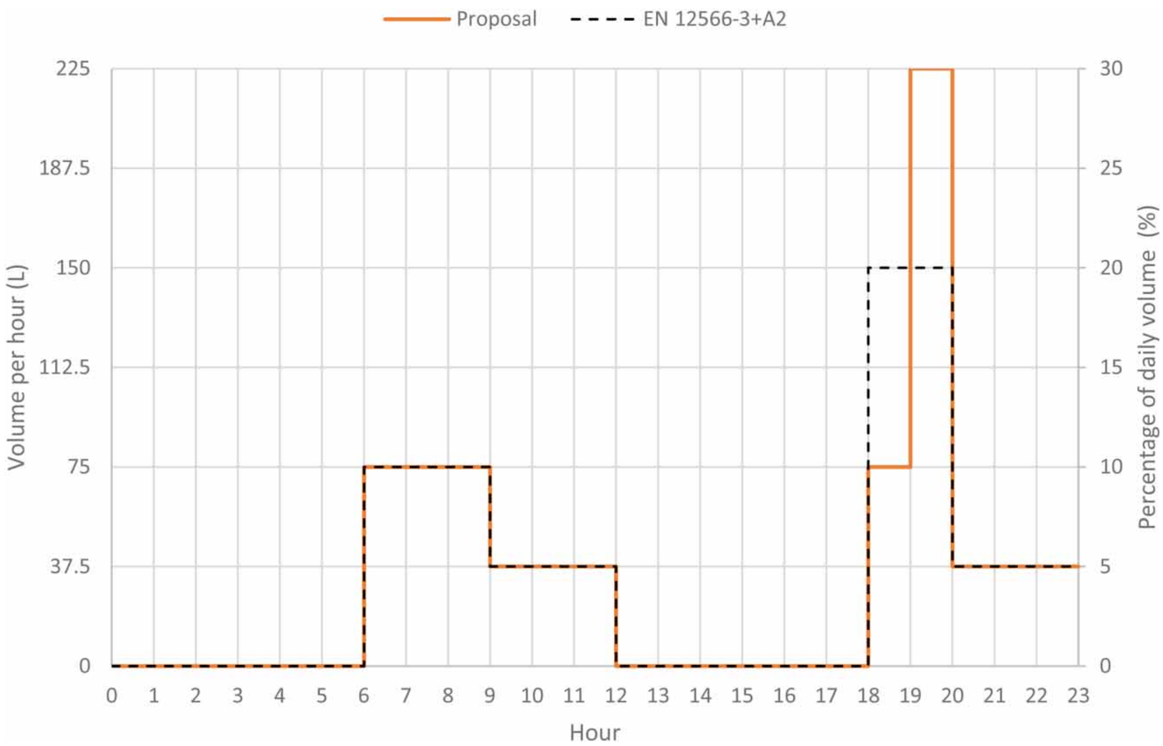


Figure 4 | Daily flow distribution during the standardized tests and proposed new distribution (these values correspond to a product of 5 PE, for a daily volume of 750 L).

[1] A "peak flow discharge" of 200 L in 3 min. It is repeated twice within a 5-min interval maximum for a product with a nominal capacity of 5 PE.

The daily organic loads ratio calculated between the *in situ* (90th percentile for an individual dwelling) and platform conditions are 1.20, 1.38 and 1.25 for SS, COD and BOD_5 respectively. They systematically indicate higher organic loads under *in situ* conditions compared to testing platform conditions. A difference stills exists between platform-measured and *in situ* organic loads but it is however lower than what is observed in terms of average concentrations in both conditions.

These various comparisons show that with dissimilar RS concentrations between standardized tests and *in situ* situation, a direct comparison of effluent concentrations between the two approaches is meaningless. However, since the organic loads measured on platform are close to the 90^{th} percentiles *in situ*, the hypothesis of similar system removal efficiencies in these two conditions seems reasonable. Such is the strategy adopted in this paper, which will include in next sections the considerations to be taken to confirm comparisons.

Removal efficiency analysis

Determination of estimated removal efficiency allowing compliance with *in situ* regulatory requirements

The minimum *in situ* removal efficiencies of OWTS allowing compliance to different treated effluent objectives for more than 80% of *in situ* situations are calculated using the 80th percentiles of the RS concentration distributions (i.e. 789 $mg{\cdot}L^{-1}$ SS, 690 $mg{\cdot}L^{-1}$ BOD_5, 1810 $mg{\cdot}L^{-1}$ COD (Dubois *et al*. in press)). These values are rounded to the nearest 0.5% and combined in Table 5.

The higher concentration thresholds selected (i.e. 60 $mg{\cdot}L^{-1}$ SS, 40 $mg{\cdot}L^{-1}$ BOD_5 and 200 $mg{\cdot}L^{-1}$ COD) merely reflect the minimum objectives usually required for centralized wastewater treatment plants. Thus, for OWTS, the high level of required efficiencies stems from higher *in situ* RS concentrations, i.e. at least 89% for an effluent quality of 200 $mg{\cdot}L^{-1}$ in COD. In some countries, regulatory requirements are already expressed in efficiency terms (e.g. 90% COD and 95% BOD_5 in Germany as an example); nonetheless, the correspondence with effluent qualities expressed in concentrations may be based on RS concentrations which are different from those used in this paper.

Consequently, to meet French effluent requirements (i.e. 30 $mg{\cdot}L^{-1}$ SS and 35 $mg{\cdot}L^{-1}$ BOD_5), a product must achieve a minimum removal efficiency of 96.0% in SS and 95.0% in BOD_5. When these requirements are compared with the average removal efficiencies measured within the framework of standardized testing (Table 2), then all products except for SAGP2 comply with the BOD_5-related criteria, but only five products (AGSFM1, AGSFM3, AGSFM4, ASP1, SAGP1) among the eight tested comply with the SS-related criteria.

Efficiency distribution modeling

To evaluate the robustness of removal efficiency measurements during standardized tests, the data distributions from each tested product are modeled using a beta law. The modeling is deliberately limited to data which are within the RS limits provided in EN 12566-3 + A2 standard in order to stay within conditions as much controlled as possible (see Material and Methods). Based on the established models, it is possible to determine the probability of occurrence of the efficiency target value estimated on platform. This exercise was performed for each product at the minimum *in situ* efficiency estimates, as determined above with respect to quality thresholds (Table 5). Results are shown in Figure 5 as well as in Appendix 1. It is assumed that the product reaches the quality threshold once its probability of requirement compliance exceeds 0.80.

The probabilistic method offers further safety by estimating which products may comply with the expected efficiency requirement with a probability above 80%. Hence, using this probabilistic method for the French effluent requirements, the products which are complying are: AGSFM1, AGSFM3, AGSFM4 and SAGP1 for SS; and AGSFM1, AGSFM3, AGSFM4, ASP1 and SAGP1 for BOD_5 (Figure 5). In comparison to the simple compliance with average efficiency values, the results show that ASP1 product does not comply with the SS criteria, and that AGSFM2 and AGSFM5 products do not comply with the BOD_5 criteria. Based on declared efficiencies (Table 2), these results suggest that minimum required *in situ* efficiencies should be increased to at least 97% in SS and 96% in BOD_5 with a probability of compliance at 0.80.

Table 5 | *In situ* requirements expressed in concentrations and removal efficiency

Expression of *in situ* requirements	SS					BOD_5					COD				
Concentration $mg{\cdot}L^{-1}$	30	35	40	50	60	20	25	30	35	40	70	100	120	150	200
Estimated removal (%)	96.0	95.5	95.0	93.5	92.5	97.0	96.5	95.5	95.0	94.0	96.0	94.5	93.5	91.5	89.0

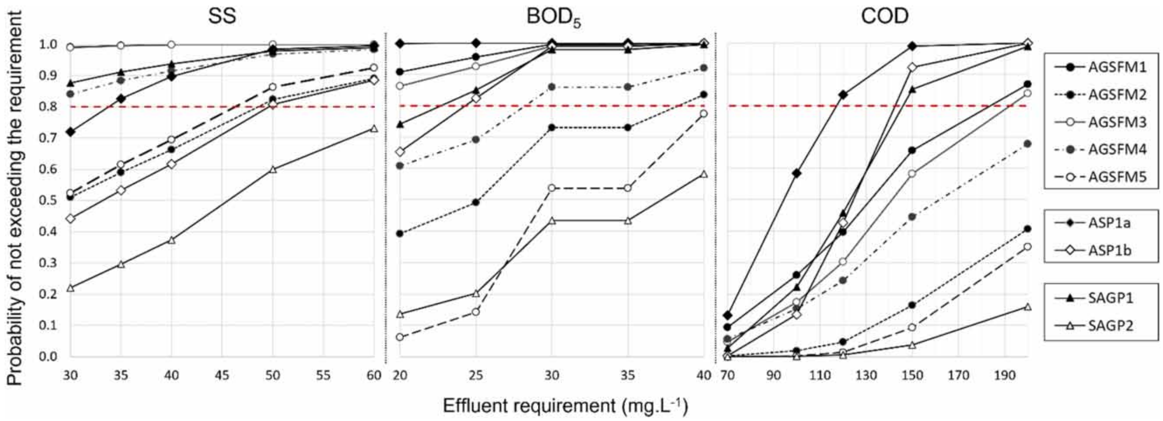


Figure 5 | Probability that the products tested comply with various effluent requirements for SS, COD and BOD_5.

Results obtained by the eight products studied can be compared with the various national regulations in effect back in 2013 in the seven European countries listed in the introduction (Dierick *et al.* 2013). Should effluent criteria include COD, then this requirement becomes the most critical. As such, for regulations including a COD threshold, namely Austria, Wallonia in Belgium, Germany and Spain, only one to three products among the eight studied actually complied with the stringent requirements, varying between 70 $mg{\cdot}L^{-1}$ and 150 $mg{\cdot}L^{-1}$ COD. Moreover, a graphic depiction of the beta law model (Figure 5) shows that none of these eight products could achieve a COD concentration lower than 120 $mg{\cdot}L^{-1}$ with a probability above 0.80. As opposed to COD, whose requirements tend to be stringent, if effluent concentrations requirement exceed 50 $mg{\cdot}L^{-1}$ SS, then all products except one (SAGP2) comply. For countries where regulations pertain to both parameters SS and BOD_5, results depend on the thresholds adopted. Hence, for Ireland and Flanders (Belgium), where requested treated effluent concentrations are 20 and 25 $mg{\cdot}L^{-1}$ BOD_5 and 60 and 30 $mg{\cdot}L^{-1}$ SS respectively, the BOD_5-based criteria is the most critical. For France however, the SS threshold proves to be critical for the highest number of products.

Additional analysis adapted to the various families of products

The efficiency-based requirements may be fine tuned for products belonging to the AGSFM family, by considering the septic tank performance and the filter performance separately. The *in situ* efficiency of septic tank is estimated based on the literature review, indicating removal efficiency from 60% to 80% for SS and from 30% to 50% for BOD_5 (U.S. EPA 2002; Siegrist 2017). For this study, the most unfavorable situation was selected for *in situ* conditions, i.e. the lowest efficiency values for each parameter: 60% for SS and 30% for BOD_5. Due to a lack of literature data, the COD removal efficiency is set equal to that of BOD_5. On the testing platform, the septic tank efficiency values available for the products studied here exhibit higher performances than those found in the literature (Table 6).

These results can be explained by the recent startup of the wastewater treatment system on the platform (within the past six months); sedimentation has taken place and helped to retain a sizable proportion of the SS. In contrast, the anaerobic degradation mechanisms, which enhance organic matter solubility, are not yet predominant due to both the small quantity of sludge stored and the product's recent startup. Accordingly, the organic matter removal efficiencies on the platform were close to the upper range of available literature data. The test on the platform is too short to establish a state of equilibrium,

Table 6 | Septic tank efficiency measured during standardized testing of the AGSFM1, AGSFM3 and AGSFM5 products, in comparison with literature data

Septic tank efficiency		SS	COD	BOD_5
In situ (literature data)		60–80%	–	30–50%
Platform results	AGSFM1	83%	54%	50%
	AGSFM3	82%	49%	45%
	AGSFM5	73%	41%	40%

which entails the two processes of physical sedimentation and water enrichment by anaerobic biological solubilization of organic matter (D'Amato *et al.* 2008).

Filter efficiency is assumed to be equivalent between the platform and *in situ* conditions. This hypothesis is verified by linear regressions correlating the surface loads applied to filters with the surface loads treated by filters, whenever data are available. For three products (AGSFM1, AGSFM3 and AGSFM5), septic tank outlet concentrations are available on the platform. Even though these products are based on three different filtering medium, a stable filter efficiency for the carbon parameters (SS, COD and BOD_5) is observed. As an example, Figure 6 depicts the regressions obtained for BOD_5 and Table 7 presents the regression coefficient values obtained for the three carbon parameters.

These results underscore the high level of regression and hence the great stability of filter efficiency for the three carbon parameters, as well as for the three products studied. This has proven to be the case also for reed bed filter-type systems (Boutin & Prost-Boucle 2015) over equivalent ranges of applied surface loads. Such results obtained with three different filtering media (one mineral material and two organic ones) can be generalized to all AGSFM family products based on aerobic degradation processes. Results however would need to be further confirmed with a wider range of materials, especially if the applied load conditions are much higher.

It is ultimately possible to link platform-measured and *in situ* efficiency by both considering the equivalency of filter efficiency between the two conditions and taking into account the differences in septic tank efficiency (Equation (3)). From this relationship, platform efficiency targets can be calculated as a function of the estimated *in situ* efficiency and various hypotheses on septic tank performance (Appendix 2). Results are shown graphically in Figure 7. As expected, the higher the septic tank efficiency measured on platform, the higher the target value of the overall product removal efficiency.

Based on the previous and the estimated *in situ* efficiency requirements to satisfy the French regulation criteria, as respectively set at 96.0% for SS and 95.0% for BOD_5 (Table 5), it is possible to estimate the required removal efficiency by introducing into Equation (3) these quantitative values along with the septic tank efficiencies under both *in situ* and platform conditions (Table 6). The exercise was conducted for the three products for which there were platform data available on septic tank efficiency. The minimum estimated platform efficiency for SS thus reaches values of 98.3%, 98.2% and 97.3%

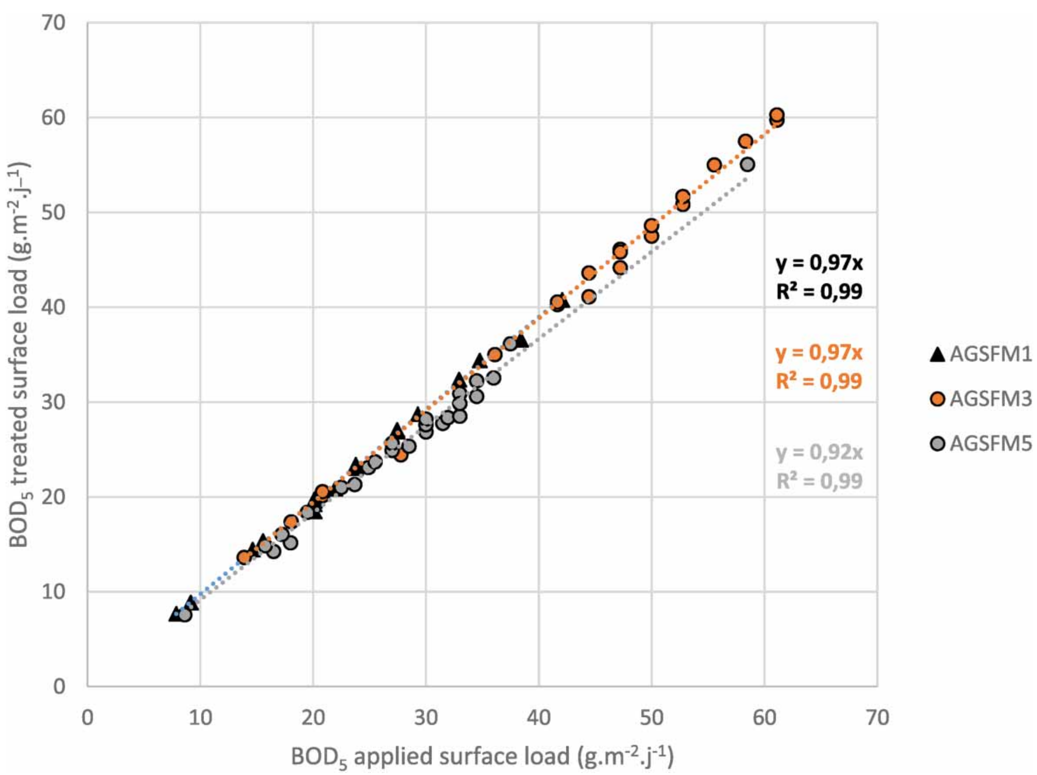


Figure 6 | Linear regressions correlating the surface loads in BOD_5 treated by filters at products AGSFM1, AGSFM3 and AGSFM5 with the corresponding applied surface loads.

Table 7 | Regression coefficients (R^2) of the linear regressions correlating the surface loads treated by filters for products AGSFM1, AGSFM3 and AGSFM5 with the corresponding applied surface loads

Product	SS	COD	BOD_5
AGSFM1	0.98	0.96	0.99
AGSFM3	0.99	0.95	0.99
AGSFM5	0.96	0.87	0.99

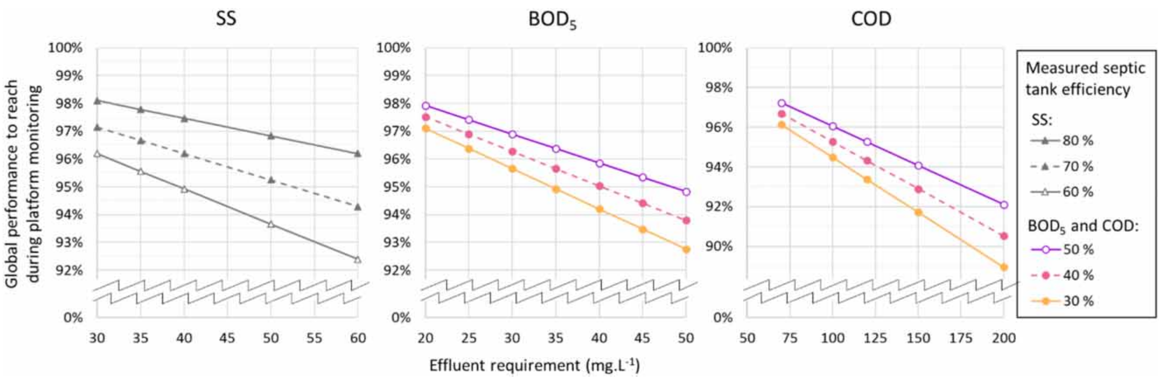


Figure 7 | Estimated platform efficiency for compliance with *in situ* regulatory requirements, vs. septic tank efficiency measured on platform.

for products AGSFM1, AGSFM3 and AGSFM5, respectively. Similarly, for BOD_5, the minimum estimated platform efficiency amounts to 96.4%, 96.1% and 95.7%, respectively. Overall efficiency measured on the platform (Table 2) indicates that products AGSFM1 and AGSFM3 always comply with the new criterion of each regulatory parameter. Moreover, the AGSFM5 product, which had already failed to comply with the SS-related minimum criteria, no longer complied with the BOD_5-related requirement, i.e. with a 95.0% efficiency measurement *versus* a fine-tuned requirement of 95.7%. Knowledge of septic tank efficiency measured on the platform allowed us to determine the thresholds to be met that correspond to *in situ* conditions and thereby enhance safety for system users and protection of the environment.

For SAGP- and ASP-product families, a more refined comparison of platform *versus in situ* performance should take into account the operating conditions as daily and hourly hydraulic peak flows, which require delicate analysis. Lower *in situ* hydraulic loads lead to longer residence times; for similar aeration periods, *in situ* performance regarding the soluble carbon fraction will be improved compared to standardized testing conditions. In contrast, the *in situ* hourly hydraulic peaks, which are higher than the daily peaks of the standardized tests, may lead to large losses of SS, thus degrading the quality of the particulate fraction in the treated effluent. This phenomenon may be amplified with a reduced sludge settling capacity. In the absence of sufficient data to compare the cumulative impacts of these two main competing effects, the most favorable conditions to achieve effluent quality cannot be identified and it is difficult to further refine the analysis. As such, the minimum requirements for estimated *in situ* efficiency (Table 5) remain as a hypothesis for the SAGP and ASP families.

The methodology presented in this paper, applied to eight products and narrowed to French requirements, is summarized in Table 8.

Products installed in France must meet the two treated wastewater quality requirements expressed in SS (30 mg·L^{-1}) and in BOD_5 (35 mg·L^{-1}) simultaneously. A comparison of the efficiency measured during standardized tests with the minimum *in situ* efficiencies, estimated from the 80^{th} percentiles at 96.0% in SS and 95.0% in BOD_5, ruled out three products (AGSFM2, AGSFM5 and SAGP2) from the eight studied. Modeling based on beta law with a probability of compliance at a minimum of 0.80 indicates that product ASP1 failed to satisfy the SS-related criteria and confirmed the non-compliance of the three same previous products. In addition, calculations using septic tank efficiency available for products AGSFM1, AGSFM3 and AGSFM5 allowed refinement in terms of efficiency required on the platform and, under these conditions, product AGSFM5 does not comply with SS and BOD_5 requirements. However, the latter approach is not applicable for other product family.

Table 8 | Application of the methodology developed in this paper for the eight products studied, for French regulatory requirements

Criterion	AGSFM1		AGSFM2		AGSFM3		AGSFM4		AGSFM5		ASP1		SAGP1		SAGP2	
	SS	BOD_5	SS	BOD_5	SS	BOD_5	SS	BOD_5	SS	BOD_5	SS	BOD_5	SS	BOD_5	SS	BOD_5
Comparison of estimated and measured efficiencies																
Prediction of removal efficiency target with a probability of 0.8																
Comparison if septic tank efficiency is available			*N/A*				*N/A*									

N/A: Not available.
Note: Cells appear in gray when the criterion has been satisfied; otherwise, they appear as hatched. Cells are left blank if the criterion analysis has not been adapted or if the particular data element is missing.

This exercise demonstrates that is possible to establish minimum *in situ* efficiencies to satisfy French requirements. Based on equivalency of efficiency between platform and *in situ* conditions, it is possible to introduce them as requirements in regulation, allowing a comparison of the declared performance of CE-marked products directly to these prescribed values. This approach can be adapted to any product and to the various effluent quality thresholds mentioned in current regulations across countries whose lifestyle can be compared with that of France, i.e. mainly in Europe but perhaps on other continents as well.

CONCLUSIONS

Aiming at fulfilling environmental and health requirements, this study has focused on OWTS performance by comparing results from standardized tests conducted on the platform and the required *in situ* performance. From differences observed between these two conditions, a methodology relying on efficiency requirements has been developed here. Results stemmed from two sources: (i) an analysis of CE-marking standardized test results available for eight products, belonging to different treatment families and tested on four European platforms; and (ii) data from a study characterizing the RS discharged by 15 French households. Based on data available, this paper has been deliberately limited to three parameters for characterizing the carbon matter (SS, COD, and BOD_5).

A comparison of the characteristics of RS used for standardized testing protocols on the platform with RS discharged from a French household led to several conclusions. RS collected from individual dwellings is more concentrated than that found for RS feeding testing platforms, by a factor of 1.5 to 1.7. The differences in hydraulic loads between the two conditions, especially peak factors (much higher *in situ*), suggest a modification in the hourly flow distribution during standardized tests to better reflect actual *in situ* conditions. The hydraulic overload conditions, associated with low concentrations during standardized tests, generate organic load conditions quite similar to those encountered at the 90th percentile of *in situ* conditions: the ratio between the two test set-ups decreases to values of 1.2 to 1.4. In conclusion, the major differences observed in RS concentrations do not allow a direct comparison of effluent concentrations for the two conditions (platform and *in situ*). In order to link these two approaches, an efficiency-based rationale is foreseen and confirmed by the smaller deviation observed between organic loads applied on the platform and the 90th percentile of the *in situ* organic load distribution. The comparability between efficiency measured on platform and that estimated *in situ* is demonstrated for the filters of AGSFM-type products and used, by extension, for SAGP- and ASP-type products.

Minimum efficiency requirement targets are estimated from field data, such that 80% of situations encountered meet the discharge objectives. These estimated *in situ* efficiency values may be calculated in each country on the basis of national discharge-related requirements. To obtain a minimum quality of 60 $mg{\cdot}L^{-1}$ SS, 200 $mg{\cdot}L^{-1}$ COD and 40 $mg{\cdot}L^{-1}$ BOD_5, the efficiency target values are thus respectively 92.5%, 89.0% and 94.0%. A comparison of these estimated efficiencies with values measured during standardized tests, as declared by the manufacturer, provides a first-level validation of a product's ability to meet national requirements.

To evaluate the robustness of performance measured on the platform, the efficiency is modeled by a beta law that determines the probability of a tested product to meet a requirement. The minimum probability was set in this paper at 0.80 to assess a product's performance as acceptable. Another probability value may be selected, with the efficiency target then being estimated from reading the available abacus.

Finally, for AGSFM-type products, it is possible to fine tune the efficiency target values estimated on platform when an intermediate measurement point is inserted between the septic tank and the filter. The additional measurement allows the establishment of a more demanding platform efficiency.

Consequently, by applying French regulatory requirements, the methodology identifies non-compliance for three of the eight products analyzed during the first step (evaluating efficiency measured on platform), and then an additional non-compliant product after the performance modeling step using beta law. Determining fine-tuned platform efficiency target values is possible for three AGSFM-type products with known septic tank efficiency, thus confirming the non-compliance with French requirements for one more product. Beyond the products studied here, this methodology can be applied not only to other national requirements but also to a larger number of products, spanning the range of treatment families. Based on equivalency of efficiency between platform and *in situ* conditions, it is possible to introduce them as requirements in regulation, allowing a comparison of directly declared performance of CE-marked products to these prescribed values.

ACKNOWLEDGEMENTS

The authors would like to thank Yves LE GAT (INRAE Nouvelle-Aquitaine Region-Bordeaux) for his support and participation in the discussions surrounding the statistical tools used in this paper.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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First received 22 October 2021; accepted in revised form 11 January 2022. Available online 25 January 2022