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 BOD5 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.

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INTRODUCTION

When a dwelling is not connected to a public sewer network, it must be equipped with ‘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 (Ayphassoroh 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 (CEN 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 thereby declare the performance of their wastewater treatment products in terms of removal efficiency. There is no threshold value related to the declared performance.

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·L⁻¹ SS, 90 to 150 mg·L⁻¹ COD, and 20 to 40 mg·L⁻¹ BOD₅. Requirements may simultaneously apply to all three carbon parameters, like in Spain, or only a couple of parameters (SS and COD or COD and BOD₅). Some countries also add an effluent requirement pertaining to ammonia nitrogen. In France, the modified decree dated September 7th, 2009 (Ministres d’Etat 2021) sets requirements as thresholds of 30 mg·L⁻¹ SS and 35 mg·L⁻¹ BOD₅. 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 revealed 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) indicates that compliance of treated effluent with the acting water 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 loads, concentrations and loads. Results from this comparison then allow proposing 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 analysed in this study come 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 different 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) suspended solids 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 AGSF3 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 nutrients.

The nominal daily volume is fed on 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·d⁻¹·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 m³·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 (AGSF1, AGSF3 and AGSF5), 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 raw sewage evaluation study involving 15 French households (Olivier et al. 2019b). 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 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:

\[ \eta_{\text{estimated in situ}} = \frac{80\text{th RS percentile} - \text{required effluent concentration}}{80\text{th RS percentile}} \]  

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 AGSF 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 AGSF-type products may be broken down as follows:

\[ \eta = \eta_{\text{septic tank}} + \eta_{\text{filter}} (1 - \eta_{\text{septic tank}}) \]  

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 BOD₅ | 14 | 19 | 19 (±3*a) | 18 | 20 | 12 | 7 | 11 | 17 |
| all b | 14 | 17 | 18 (±2*b) | 18 | 11 | 12 | 7 | 10 | 15 |

*aAdditional samples.

bParameters: SS, COD and BOD₅, NH₃-N, KN and TP.
it is possible to establish a correlation between platform efficiency and in situ efficiency, i.e.:

\[ \eta_{\text{estimated on platform}} = \eta_{\text{platform septic tank}} + (1 - \eta_{\text{platform septic tank}}) \times \frac{\eta_{\text{estimated in situ}} - \eta_{\text{in situ septic tank}}}{1 - \eta_{\text{in situ septic tank}}} \]  

Taking conventional values of in situ septic tank removal efficiency from literature (U.S. EPA 2002; Siegrist 2017) along with the septic tank removal efficiency measured on 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 80\(^{th}\) 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:

- Lower fence: Q1 – 1.5 × EI
- Upper fence: Q3 + 1.5 × EI

| Platform | P1 | P2 | P3 | P4 |
|----------|----|----|----|----|
| Product  | AGSF1 | AGSF2 | AGSF3 | AGSF4 | AGSF5 | 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 |

**Figure 1** | 'Boxplot' type display of a data distribution.
Upper fence: $Q_3 + 1.5 \times EI$

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 in the case where 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:

$$H_0: \text{'No difference exists between the samples.'}$$

The test determines the probability $p$ (p-value) of erroneously rejecting the null hypothesis $H_0$. This hypothesis is not accepted if the $p$-value lies below the significance threshold $\alpha$, typically set at 5%. If hypothesis $H_0$ 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 calculating 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, $\alpha$ and $\beta$ (Forbes et al. 2010). Data are modeled with the R software thanks to the fitdist() function. The pbeta(real, $\alpha$, $\beta$) 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.

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 BOD₅ 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 BOD₅ 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 BOD₅ concentrations are identified: COD concentrations in the effluent feeding platform P1 are higher than those feeding platform P3; as for BOD₅, 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 BOD₅, deviations between average RS concentrations among the various test platforms do not exceed 14% for COD and 18% for BOD₅. 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/BOD₅ ratio of platform P1 is different and higher than that of the three other platforms. The COD/BOD₅ 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

| Measurement conditions | Average concentrations (mg·L⁻¹) | Average ratios |
|------------------------|-------------------------------|----------------|
|                        | SS | COD | BOD₅ | COD / BOD₅ | COD/SS |
| Platform P1            | 380 | 747 | 309   | 2.5        | 2.0    |
| Platform P2            | 391 | 729 | 347   | 2.1        | 1.9    |
| Platform P3            | 352 | 653 | 295   | 2.3        | 2.1    |
| Platform 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    |
SS, 1.72 for COD and 1.58 for BOD₅. Since the in situ RS is more concentrated (on average: 544 mg·L⁻¹ SS, 1,212 mg·L⁻¹ COD, 514 mg·L⁻¹ BOD₅), 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 2019), 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) | SS       | COD | BOD₅ |
|--------------------------------------------|------------------------|----------|-----|------|
| Platform: average loads for 5 PE           | P1                     | 733      | 261 | 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 (Olivier et al. 2019b) | | 568 | 305 | 676 | 281 |

**Figure 3** | Comparison of SS, COD and BOD₅ 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.
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 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 peak1 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](http://iwaponline.com/wst/article-pdf/doi/10.2166/wst.2022.025/990558/wst2022025.pdf)

**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).

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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 BOD₅ respectively. They systematically indicate higher organic loads under in situ conditions compared to testing platform conditions. A difference still 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 90th 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·L⁻¹ SS, 690 mg·L⁻¹ BOD₅, 1810 mg·L⁻¹ COD (Olivier et al. 2019b)). These values are rounded to the nearest 0.5% and combined in Table 5.

The higher concentration thresholds selected (i.e. 60 mg·L⁻¹ SS, 40 mg·L⁻¹ BOD₅ and 200 mg·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·L⁻¹ in COD. In some countries, regulatory requirements are already expressed in efficiency terms (e.g. 90% COD and 95% BOD₅ 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·L⁻¹ SS and 35 mg·L⁻¹ BOD₅), a product must achieve a minimum removal efficiency of 96.0% in SS and 95.0% in BOD₅. 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 BOD₅-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 modelling is deliberately limited to data which are within the RS limits provided in EN 12566-3+A2 standard so as 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 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 BOD₅ (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 BOD₅ 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 BOD₅ 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 | BOD₅ | COD |
| Concentration mg·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 | 94.0 | 94.5 | 93.5 | 91.5 | 89.0 |
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 comply with the stringent requirements, varying between 70 mg·L$^{-1}$ and 150 mg·L$^{-1}$ COD. Moreover, a graphic depiction of the beta law model (Figure 5) shows that none of these eight products can achieve a COD concentration lower than 120 mg·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·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·L$^{-1}$ BOD$_5$ and 60 and 30 mg·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 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 testing platform, the septic tank efficiency values available for the products studied herein exhibit higher performances than those found in literature (Table 6).

These results can be explained by the recent startup of the wastewater treatment system on platform (within the past six months); sedimentation has taken place and helped retain a sizable portion of 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 platform are close to the upper range of available literature data. The test on platform is too short to establish a state of equilibrium, 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 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 is available. For three products (AGSFM1, AGSFM3 and AGSFM5), septic tank outlet concentrations are available on platform. Even though these products are based on three different filtering medium, a stable filter efficiency for the carbon parameters (SS, COD and BOD5) is observed. As an example, Figure 6 depicts the regressions obtained for BOD5 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 process. 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 BOD5 (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 is conducted for the three products which have platform data available on septic tank

![Figure 6](http://iwaponline.com/wst/article-pdf/doi/10.2166/wst.2022.025/990558/wst2022025.pdf)
efficiency. The minimum estimated platform efficiency for SS thus reaches values of 98.3%, 98.2% and 97.3% 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 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 complies 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 platform allows 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-products 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 standardized tests, may lead to large losses of suspended solids, 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 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 below.

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 80th percentiles at 96.0% in SS and 95.0% in BOD$_5$, has 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 is failing to satisfy the SS-related criteria and confirms the non-compliance of the three same previous products. In addition, calculations using septic tank efficiency available for products AGSFM1, AGSFM3 and AGSFM5 allows refinement in terms of efficiency required on platform and, in those conditions, product

| 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.

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
AGSFM5 does not comply with SS and BOD₅ requirements. However, the latter approach is not applicable for other product family.

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 to compare 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 platform and required in situ performance. From differences observed between these two conditions, a methodology relying on efficiency requirements has been developed herein. 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 characterizing the carbon matter (SS, COD, and BOD₅).

A comparison of the characteristics of RS used for standardized testing protocol on platform with RS discharged from a French household allows several conclusions. RS collected from individual dwellings is more concentrated than 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 in 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 platform and the 90th percentile of the in situ organic load distribution. The correspondence 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·L⁻¹ SS, 200 mg·L⁻¹ COD and 40 mg·L⁻¹ BOD₅, 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 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 to establish 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 herein, 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 to compare directly declared performance of CE-marked products to these prescribed values.

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DATA AVAILABILITY STATEMENT

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

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