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Modelling the benefits of urine source separation scenarios on wastewater treatment plants within an urban water basin

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ABSTRACT

Stringent discharge regulations are encouraging researchers to create innovative and sustainable wastewater treatment solutions. Urine source separation (USS) is among the potent approaches that may reduce nutrient peak loads in the influent wastewater and improve nutrient recovery. A phenomenological model was used to simulate dynamic influent properties and predict the advantages gained from implementing USS in an urban water basin. Several scenarios were investigated assuming different levels of deployment: at the entire city, or specifically in office buildings for men's urine only, or for both men and women employees. The results confirmed that all scenarios of urine source separation offered benefits at the treatment plant in terms of reducing nitrogen influent load. The economic benefits in terms of reducing energy consumption for nitrification and decreasing methanol addition for denitrification were quantified, and results confirmed environmental advantages gained from different USS scenarios. Despite larger advantages gained from a global USS rate in an entire city, implementation of a specific USS in office buildings would remain more feasible from a logistical perspective. A significant benefit in terms of reducing greenhouse gas emissions is demonstrated and this was especially due to the high level of N_2O emissions avoided in nitrifying biological aerated filter.

Key words: influent generator, nitrogen removal, urine source separation, wastewater treatment

HIGHLIGHTS

- A methodology for modelling different urine separation scenarios in an urban area is shown.
- An influent generator was calibrated and gives the variation of effluent quality.
- Savings in aeration and methanol are quantified at the treatment plant.
- Important reduction of greenhouse gas emissions is shown for different recovery techniques.
- The benefits are related to the reduction in N_2O emissions and N fertilizer substitution.

1. INTRODUCTION

Nowadays, cities stakeholders and utilities have to face multiple challenges related to wastewater treatment. Limiting nutrients discharge is still a priority for protecting large river basins from eutrophication, while energy saving and nutrients recovery are increasingly needed. According to the Water Framework Directive of the European Union, Paris utilities invest tremendous effort to obtain low nitrogen concentrations in the effluents rejected from treated wastewater emerging from the city, to insure the good surface water status of the Seine River. Yet, optimization of nitrogen removal in intensive nitrifying and denitrifying biological active filters is still a complex challenge, while the high loading rate and variation of carbon source affect both nitrite accumulation (Rocher *et al.* 2015) and N_2O emissions (Bollon *et al.* 2016). A regular retrofitting of existing wastewater treatment plants (WWTP) could help tackle the problem, but alternative approaches such as urine source separation (USS) is also considered (Guest *et al.* 2009; Larsen *et al.* 2009). Despite the theoretical advantages of source separation, stakeholders and utilities need planning tools and scenarios assessment for successful implementation of USS technology, especially in a large city such as Paris with various urban typologies and densities.

Urine separation gained wide merit as it could simultaneously reduce nutrient loads and help in recovering valuable nutrients from the separated waste streams (Larsen *et al.* 2013; Jimenez *et al.* 2015; Flanagan & Randall 2018; Volpin *et al.* 2018; Spuhler *et al.* 2020). In the last decade, innovative technologies for nutrients recovery from urine were investigated and are still under development (Larsen *et al.* 2021). Nitrogen and phosphorus were recovered using electrodialysis (De Paepe *et al.* 2018; Volpin *et al.* 2020), forward osmosis (Volpin *et al.* 2019; Courtney & Randall 2022) or bio-electrochemical systems (Zamora *et al.* 2017; De Paepe *et al.* 2020; Liu *et al.* 2022). Nitrification-denitrification was also studied (Udert & Wächter 2012), as well as magnesium dosage to achieve struvite precipitation from source separated urine (Hug & Udert 2013; Udert *et al.* 2016). The most mature solution is based on combined partial nitrification and distillation which allows to convert urine into a nutrient rich solution that can be used as a fertilizer (Fumasoli *et al.* 2016). Otherwise, solutions that are still under development consist of two-step processes including struvite precipitation and ammonia recovery as ammonium sulfate using microbial electrolysis cell (MEC) (Igos *et al.* 2017) or transmembrane chemisorption (TMCS) (Pradhan *et al.* 2019; Gonzalez-Salgado *et al.* 2020; Besson *et al.* 2021). These technologies offered promising results, however their implementation was, in the majority, limited to lab-scale and pilot-scale.

Urine source separation should be further considered for its potential consequences at the wastewater treatment plant. Considering all the constraints and objectives to be considered for WWTP management, reducing overall operating costs (chemicals and energy) is a complex challenge for operators (Azimi & Rocher 2017). The most advanced approaches focused on multiple control strategies to reduce specifically the aeration costs (Varhelyi *et al.* 2018), the methanol addition as an external carbon source for denitrification, or iron dosage (Kazadi Mbamba *et al.* 2019). Urine contributes almost 80% of the nitrogen and 50% of the phosphorus to the total nutrients load in the influent wastewater (Larsen & Gujer 1996). Consequently, adopting a USS based approach could diminish and modify the pattern of nutrients load that arrives at the WWTP, helping operators to save energy for aeration and chemical consumption for nitrogen and phosphorus removal (Ishii & Boyer 2015; Jimenez *et al.* 2015). The potential benefits of urine source separation (USS) was globally assessed by life cycle analysis and costs analysis (Bisinella de Faria *et al.* 2015; Igos *et al.* 2017), using average data in the context of European countries. However recent work has also demonstrated the importance of urbanism typology in the assessment (Besson 2020; Besson *et al.* 2021), making it crucial to consider local information for each case-study.

For benchmarking source separation scenarios, a dynamic influent generator (Gernaey *et al.* 2011) was recently adapted for modelling the modification of wastewater composition depending on urine separation strategies (Bisinella de Faria *et al.* 2020). Previously, simulation studies confirmed the importance of modelling tools to assess multilevel urine separation (Rauch *et al.* 2003; Rossi *et al.* 2009). A stochastic model was used to predict urine production and to provide detailed information about the dynamics at a local level while implementing a source separation scenario, and concluded an almost 30% reduction in the ammonia peak loads during dry weather periods (Rauch *et al.* 2003). In addition, researchers performed the life cycle assessment of urine source separation, and their findings helped in the design of future applications of urine source separation through the extrapolation of their analysis to an entire watershed (Rossi *et al.* 2009; Ishii & Boyer 2015; Badeti *et al.* 2021; Hilton *et al.* 2021). With the recent adaptation of the influent generator, researchers proposed a more deterministic tool for investigating and implementing various source separation scenarios at the city scale (Bisinella de Faria *et al.* 2020; Besson *et al.* 2021). The implementation of urine source separation needs large case studies that could identify all of the pros and cons that may emerge from urine source separation. If the advantages of such a strategy seem numerous, they have to be compared to the constraints of collection, transport and treatment of the urine collected separately (Boyer & Saetta 2019). Therefore, it is essential to use simulation approaches for assessing real case studies, which would help in defining and building the appropriate scenarios for urine source separation.

Previous studies in the literature focused on urine source separation at large scale without considering the location and the potential use of buildings, despite the fact that it is less costly to implement urine separation in offices using a reduced number of toilets for a large volume of urine collected. Moreover, no study has focused on the effect of area of collection and the length of the sewer on the influent pattern at the wastewater treatment plant.

The aim of this study was to assess the urine source separation scenario in a large urban watershed (Marne Aval, MAV, eastern Paris) considering different implementation strategies. A modelling tool was calibrated considering sewer characteristics, number of inhabitants and typology. Different implementations are compared either in households or in working buildings. Modification of dynamic wastewater patterns are calculated and benefits are concluded in terms of aeration costs and chemical consumption at the wastewater treatment plant. Finally, global estimations of greenhouse gas emissions and energy consumption are determined and discussed.

2. MATERIALS AND METHODS

2.1. Scenarios for urine source separation

The Marne Aval (MAV) urban catchment, situated in the eastern part of Paris, generates the wastewater of 210,123 population equivalents (PE). This area is divided into 16 subareas and 62% of them have a separate rainwater collection. The working population corresponds to around a quarter of the PE (offices, working buildings) whereas three-quarters of the total PE are assumed to be households (house and residential buildings). The wastewater is transported and treated by the SIAAP (Greater Paris Sanitation Authority) at the Marne Aval Wastewater Treatment plant (MAV Plant). In the current study, the active working population was assumed to be equally divided between men and women. For simulating urine source separation, two typologies of implementation were compared: a homogeneous urine separation deployed in the entire city at various levels (both households and office buildings), and a more selective option with urine separation installed in working areas and office buildings (Table 1). For the first option, different levels of deployment were calculated (20, 40, 60%) for estimating the proportionality of the benefits. The intermediate level (40%) was used in this paper and named 'scenario 1' for comparison with source separation at the work place.

Two specific scenarios (named scenario 2 and 3) were considered for urine separation at work places and during work hours only (between 8:00 a.m. and 5:00 p.m.). Scenario 2 simulated the collection of 90% of men urine at work places using urinals (men workers estimated at 26,265 PE), assuming that during work hours toilets are mainly used for urination. This scenario focuses on male urine because of the greater availability of dry male urinals on the market, although female urinals also exist. The scenario is still valid for a mix of male and female urinals. Finally, scenario 3 corresponds to 90% urine source separation of all employees (men and women estimated at 52,530 PE), using diverting toilets, which are assumed to be very efficient in source separation (Table 1). Dry urinals were considered without any flush volume, whereas reduced volumes of water were considered for diverting toilets (Bisinella de Faria *et al.* 2020).

2.2. Parameterization of the influent generator for urine separation

This study was conducted using the phenomenological influent generator (Gernaey *et al.* 2011) that was specifically modified to include urine source separation (Bisinella de Faria *et al.* 2020), and modified to consider the production from the work place. The tool is programmed on Matlab and is a flexible simulation tool that can be easily modified. The code is available on request from the author. In this study, the results were selected to represent typical weeks during dry weather periods.

Four main streams were defined in the influent generator (different blocks): 1) the Total Wastewater stream (TWW) that includes wastewater from households, industries and other contributors without any urine separation; 2) the Total Urine stream (TU) that simulates profiles of all produced urine; 3) the Urine Stored and Collected stream (USC) that corresponds to the user-specific urine source separation and collection; and 4) the Wastewater stream (WW) that represents the influent entering the treatment plant and represents the combined contribution from households, industries, rainfall, and infiltration (Bisinella de Faria *et al.* 2020). In addition, the influent generator was modified to create the composition of urine that would be collected in different buildings, such as residential buildings, houses or even office buildings. Regarding the simulations of different scenarios of USS, the user can define the general parameters according to the supposed scenario and accordingly defines the percentage of urine retention and the size of the catchment area. Also, it is possible to modify the flush water volumes for urine source-separated toilet (New flush water), to simulate USS using men urinals or low flush toilets (Bisinella de Faria *et al.* 2020).

Dynamic flow patterns were generated for daily profiles, weekly profiles and yearly profiles. For the influent wastewater entering the treatment plant, two major peaks were distinguished, around 8:00 a.m. and 6:00 p.m. (Langergraber *et al.*

Table 1 | Detailed description of the three simulated scenarios for urine source separation

	Scenario 1	Scenario 2	Scenario 3
Urine retention level	40%	90%	90%
Type of separation	Global: entire population	Specific: men employees	Specific: all employees
Corresponding population	210,123 PE	26,265 PE	52,530 PE
Suggested separation toilets	Diverting toilets	Men urinals	Men urinals, Diverting and vacuum toilets

2008). In the current study and during several set of simulations, the average total wastewater flowrate (TWW) from households was considered to be 209 $L.PE^{-1}.d^{-1}$, while the average urine flowrate was equal to 1.36 $L.PE^{-1}.d^{-1}$ (Bisinella de Faria *et al.* 2020).

For scenarios 2 and 3, the coefficients of wastewater (WW) and urine (USC) profiles were modified to simulate the collection of urine at work places, between 8:00 a.m. and 5:00 p.m. (from Monday to Friday). For both of the standard (normal production) and modified profile generation (during work hours), user defined profiles were scaled to 1, to avoid major differences in the influent load and to create reproducible profile generation as for normal wastewater and urine production (Figure 1). The profile of urine generation at work places has been assumed to be constant during working hours, due to lack of relevant data on urination pattern during the day. On average, the total volume of urine produced daily was equal to 1.36 liters (Rauch *et al.* 2003; Rossi *et al.* 2009), of which one-third was integrated in the calculation for profile production at work (Jönsson *et al.* 2005). The resulting wastewater influent profile was obtained by subtracting the separated urine at work from the regular profile produced on a daily basis before the modelling of the sewer, for scenarios 2 and 3.

2.3. Calibration of the influent generator to sewer characteristics

For the set-up of the influent generator, several hydraulic parameters needed to be calibrated specifically regarding the size and characteristics of the catchment area. Indeed, the wastewater residence time in the sewer increases with the surface of the catchment area, and leads to delaying and buffering of the diurnal peaks. In this work, the hydraulic parameters were adapted in order to obtain a sufficiently good prediction of influent flowrates profile measured at the MAV Plant. The influent generator describes the sewer network by a number of interconnected pipes and reservoir tanks that correspond to a number of 'subareas'. A subarea is defined by a surface A (m^2) corresponding to the surface of each aforementioned collection tank (Gernaey *et al.* 2011). Consequently, the number of subareas and their surface are two specific parameters that needed to be identified for each catchment area depending on its size and properties. A series of simulations were conducted successively, to identify the appropriate number of subarea and the tank surfaces A (m^2) that best fit the measured wastewater profile entering to the treatment plant. Statistical analysis based on the normalized root-mean-square deviation (NRMDS) and R^2 methods were used to compare the simulated profiles and the experimental one (Fig S2). A number of subareas of (seven) and a tank surface of 2000 m^2 corresponded to the optimal set of parameters (Tables S1 and Table S2).

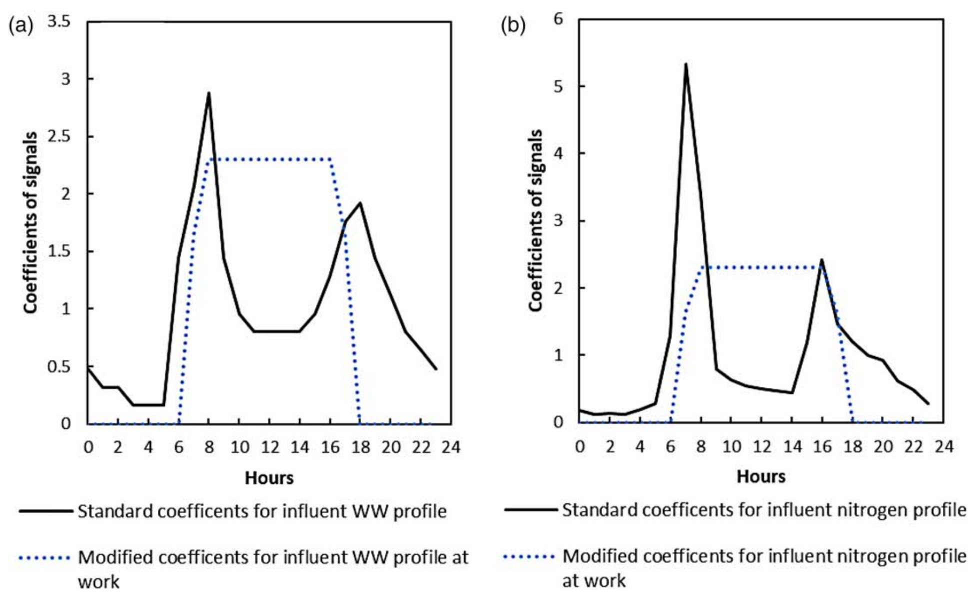

Figure 1 | Standard and modified coefficients for wastewater profile generation (a) and for nitrogen production (b), which simulates urine generating profiles. Normal profile production are typically characterized by a morning peak production around 8:00 a.m. and another peak production in the afternoon, around 6:00 p.m. The modified profile generation target production during working hours only, between 8:00 a.m. and 5:00 p.m.

2.4. Calculation of aeration needs and methanol addition

The modification of nitrogen and COD influent loads were used to estimate the reduction in aeration needs (nitrification) and methanol consumption (denitrification). Reference data were obtained from the plant operators of MAV: extensive measurements of influent ammonium, wastewater flow rates, methanol dosing and aeration flow rate were recorded with high frequency. The wastewater treatment plant is equipped with two stages of biofilters to achieve nitrification and denitrification of the influent wastewater. The first stage of biofilters (DN/N with internal recirculation of 100% of the influent flowrate) achieves 90% nitrification. The second stage of biofilters (DN with external carbon source) achieves the post-denitrification to reach 4.5 mgNO_3-N/L (effluent setpoint) with an average methanol dosage of 3.43 kg MeOH/kg N-NO_3 removed. These ratios were used to calculate the potential savings at the treatment plant for each scenario of urine separation. The oxygen demand for nitrification and COD removal were calculated based on the concentration in the rejected effluent at 45 mg COD/L, 3.5 mg NH_4-N/L and 4.5 mg NO_3-N/L. The details of calculations are available in section 3 of the Supplementary Information.

2.5. Sensitivity of influence of catchment size

In order to investigate the sensitivity to the size of the watershed, a different watershed simulation was performed using three subareas and a tank surface of 2000 m^2. The number of PE treated was reduced by a factor 3/7. This factor is equal to the reduction ratio between the new number of subareas (three) compared to the default one (seven). The scenario without source separation and scenario 1 and 3 were simulated. The results in terms of ammonium mass flow entering the WWTP, the aeration need and the methanol use are discussed hereafter. It should be noted that the variation of subareas etc. only influences the peaks and not the averages.

2.6. Calculation of greenhouses gases emissions

The overall impact of each urine diversion scenario on global warming potential was calculated. For this purpose, the effects on the treatment plant operation (reduction of energy consumption, chemicals consumption, direct emission of greenhouse gases) was translated into global warming potential thanks to the Ecoinvent database (Wernet *et al.* 2016) (see Table S4 in the Supplementary Information for detailed emissions factors). The following aspects were considered:

- **The avoided energy consumption for aeration of nitrifying biofilters** was calculated with reference to the current air consumption in the plant (333 Nm^3/kg NH_4-N removed) and the oxygen demand calculated for the reference. French electricity mix was used (0.109 kgCO_2-eq/kWh) from Ecoinvent database (see Supplementary Information section 3 for detail of the calculation).
- **The avoided emission of nitrous oxide from nitrifying biofilter into air** equivalent to 0.0245 kgN-N_2O/kg$N_{nitrified}$ (Bollon *et al.* 2016) (in average for winter and summer campaign in another Parisian WWTP). The emissions of nitrous oxide dissolved in the effluent are not considered in this study.
- **Urine transport** with weekly truck collection and 10 km of distance (round trip).
- **The direct and indirect GHG emissions for three alternative technologies for urine treatment**: (1) the VUNA process which consists of a nitrification of urine followed by distillation (Fumasoli *et al.* 2016), (2) the ValuefromUrine technology with struvite precipitation and ammonia recovery by microbial electrolysis cell (MEC) (Igos *et al.* 2017), and (3) the struvite precipitation followed by the nitrogen recovery by transmembrane chemisorption (Besson *et al.* 2021). Nitrous oxide emissions from partial nitrification in the VUNA process were also considered with the preliminary result of 0.007 kgN_2O/kg-Nurine (Faust *et al.* 2021), and were integrated in the urine treatment impact. The emissions during storage (estimated at around 0.008 kgN_2O/kg-Nurine) was assumed to be prevented by the storage strategy proposed by (Faust *et al.* subm.). In this strategy, nitrified urine is fed directly on the granular activated carbon filter and not stored beforehand. For the three processes, only the GHG emissions for the treatment are considered (energy consumption, chemicals…) and not the use of the products.
- **The avoided fertilizers production** replaced by the use of products from urine was also considered with ammonium nitrate and triple superphosphate substitution.

Several other aspects were not considered: the transport of products before fields application, the emissions into air of urine-based fertilizers and conventional fertilizer; the change of pumping energy consumption in the WWTP. Finally, as the AluFer (aluminium and ferric chloride) addition is performed for removal of the suspended solid in the preliminary clarifier and not for phosphorus removal, no reduction of its consumption were considered.

In order to generalize the results to other case studies, a sensitivity analysis was performed on two parameters: (1) the N_2O emissions factors in the WWTP were modified for the one measured in activated sludge (0.0058 $kgN_2O\text{-}N/kgN_{in}$ (Bollon *et al.* 2013)), and (2) the European electricity mix (0.38659 $kgCO_2$-eq/kWh) where less nuclear energy is used and the production of electricity generates more GHG emissions.

3. RESULTS

3.1. Scenario 1: Global urine separation in Marne-Aval area

The first scenario was the homogeneous implementation of a urine source separation (USS) in the catchment area of MAV containing 210,123 PE (households, residential buildings and office buildings). Figure 2 shows the comparison of simulated influent ammonium load at the treatment plant for reference situation without urine retention, and with urine separation for 40% of the population. Table 2 summarizes the average influent wastewater and nitrogen flows for the different scenarios. Days were randomly selected during dry weather periods, to represent the evolution of nitrogen influent flows over 10 days. The average ammonium load is $2.65 \pm 0.86\ 10^3$ kg/d without urine retention and was reduced to $1.85 \pm 0.59\ 10^3$ kgN/d with urine separation as per scenario 1 (S1) (Figure 2 and Table 2). During the day the reduction percentage in ammonium loads varied between 28.9 and 31.0% (Figure 2). These reductions were more pronounced during weekdays compared to weekends. The highest reduction rate was synchronized with the highest nitrogen peak load (Figure 2). However, for homogeneous implementation (this scenario 1), the fluctuations in percentage of reduction with time are not that significant. As expected, results show that the global deployment of USS for 40% population logically leads to an important and proportional reduction in nitrogen load at the inlet of the WWTP.

Moreover, urine separation has a significant effect on the influent COD:N ratio. As shown (Figure 2(b) and Table 2), this ratio changed dynamically and on average increased from 8.1 (without USS) to 10.3 (with 40% USS). This change in the COD:N ratio was considered in the calculation of denitrification and nitrification demands at the treatment plant (recirculation, air consumption, methanol) in the estimations of benefits gained from implementing a USS scenario.

3.2. Sensitivity to level of deployment and urban surface area

The sensitivity of the results to the level of urine separation was also assessed using the same hypothesis as the one in scenario 1. Figure 3 presents the simulation results from the comparison of three different global urine retention rates, 20% USS, 40% USS and 60% USS in the Marne-Aval watershed, with the reduced ammonium influent load and the percent reduction in aeration and methanol. These results show that important reductions of nitrogen influent loads were obtained,

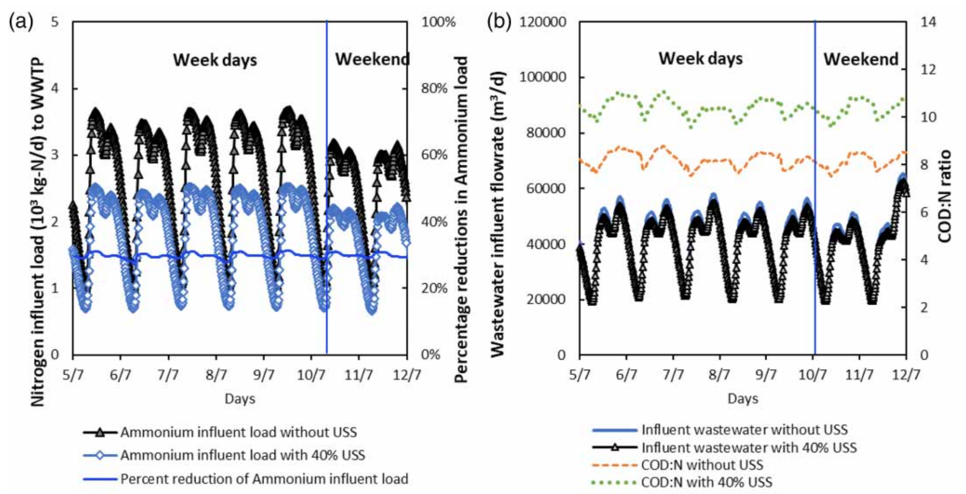

Figure 2 | (a) Flows of ammonium influent loads (10^3 kgN/d) and the percentage of reduction in ammonium influent at the WWTP; (b) Wastewater influent flowrates (m^3/d) along with the COD:N ratios, without urine source separation (USS) and with 40% USS rate, for the MAV plant and for scenario 1 (S1).

Table 2 | Summary of simulated scenarios, average daily influent flow and nitrogen flows, with and without urine source separation

	Reference MAV Plant characteristics Without USS	Scenario 1 (S1) Global implementation	Scenario 2 (S2) Work area men urine	Scenario 3 (S3) Work area men and women
Urine source separation (USS) rate	0	40%	90% of 26 265PE	90% of 52 530 PE
Mean influent flow rate (m^3/d)	43 ± 11	41 ± 10	43 ± 11	42 ± 11
Mean ammonium load (10^3 kgN /d)	2.7 ± 0.9	1.9 ± 0.6	2.6 ± 0.8	2.5 ± 0.8
Average COD:N ratios	8.1	10.3	8.2	8.34
Urine volume to collect (m^3/d)	0	171	8	24

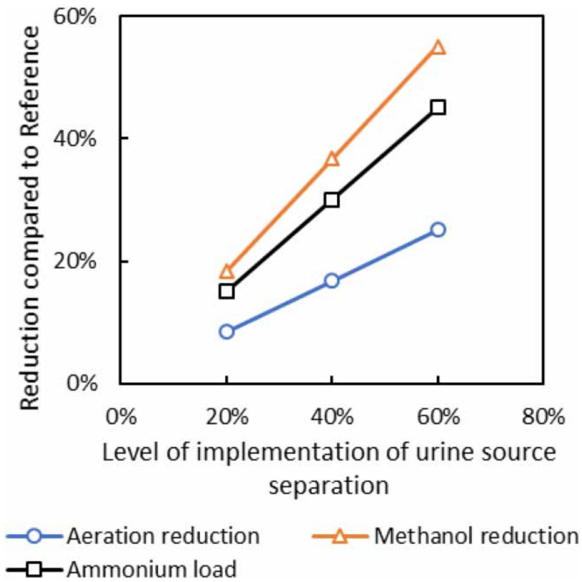

Figure 3 | Comparison of reduction need of methanol, aeration and ammonium load entering the wastewater treatment plant, for scenarios with 20, 40 and 60% urine separation rate.

which increased progressively and proportionally with the increase of the selected USS rate from 20% USS to 60% USS (see also Fig S3). Moreover, at 60% USS rate, the average reduction in the ammonium influent load could reach 1.45 10^3 kgN /d. The reductions in aeration demand and methanol addition were also proportional to the increased level of urine source separation implementation (Figure 3). Yet, the implementation of 60% urine retention rate in the entire city remains challenging from a logistical and infrastructure aspect.

Another question is the sensitivity to the size of the watershed and the level of centralization of the treatment plant. To evaluate this sensibility, a simulation was performed in a smaller watershed. Simulations (Fig S4) showed the MAV watershed presented two ammonium load peaks that had approximately the same intensity, however the smallest watershed had a more intense morning peak and a smaller evening peak. With Scenario 1, the urine source separation allowed reducing the first peak to the same level as the second peak from the reference scenario for the small watershed (Figure S4), hence the treatment plant can be designed with a treatment capacity for the second peak and not the morning one. For instance, the air supply in the small watershed without USS should be designed for the peak demand of 34,000 Nm^3/h, whereas the average demand is 15,000 Nm^3/h. With urine source separation implemented, the air compressors would need to produce 27,500 Nm^3/h to ensure appropriate treatment.

3.3. Scenario 2 and 3: Urine separation at work

Figure 4 presents the nitrogen influent loads for scenarios 2 and 3 in comparison with the reference situation. Regarding these scenarios, the urine diversion is assumed only during work hours and on work places. Logically, the effect on nitrogen load is

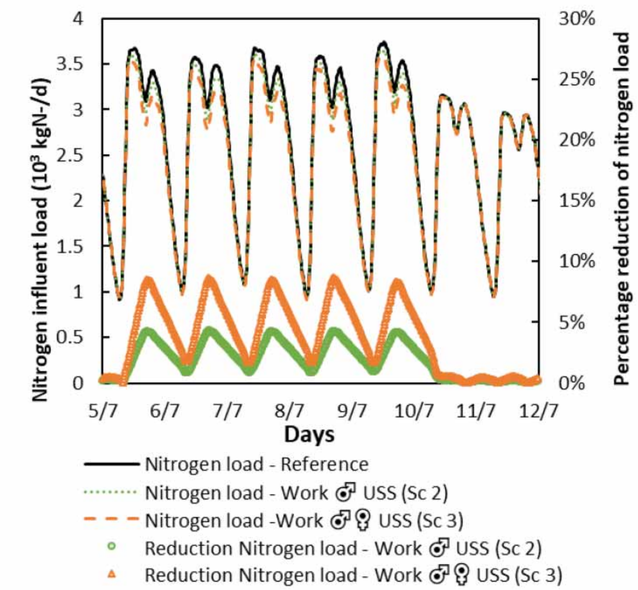

Figure 4 | Nitrogen influent load for MAV Plant for reference scenario (without USS) and for urine source separation scenarios 2 (men urinals) and 3 (all toilets) at work and their corresponding percentage reduction in nitrogen influent load.

much more dynamic compared to an homogeneous deployment (scenario 1), and the nitrogen load reduction would be naturally more pronounced during work hours. For instance, the selective retention of men urine at work (Scenario 2) showed that the nitrogen reduction factor varied between 0% (night) and 4.5% (around 4 p.m.) during a typical week day. When urine separation was considered for all working people (scenario 3, men and women), the amplitude was more pronounced and the maximal nitrogen load reduction reached 9.1% in the afternoon (Figure 4). Finally, the average influent nitrogen load reached respectively $2.58 \pm 0.83\ 10^3$ kgN/d for scenario 2 and $2.52 \pm 0.80\ 10^3$ kgN/d for scenario 3 (Table 2), which corresponds to 2.4 and 4.8% reduction of the influent nitrogen load compared to the reference scenario (current situation without any USS).

3.4. Reduction in aeration and chemical consumption

Figure 5 presents the daily variation of air flow required to achieve nitrification in the nitrifying biofilter, and the methanol dosing needed to ensure denitrification in the post-DN biofilter in the wastewater treatment plant of Marne Aval (MAV).

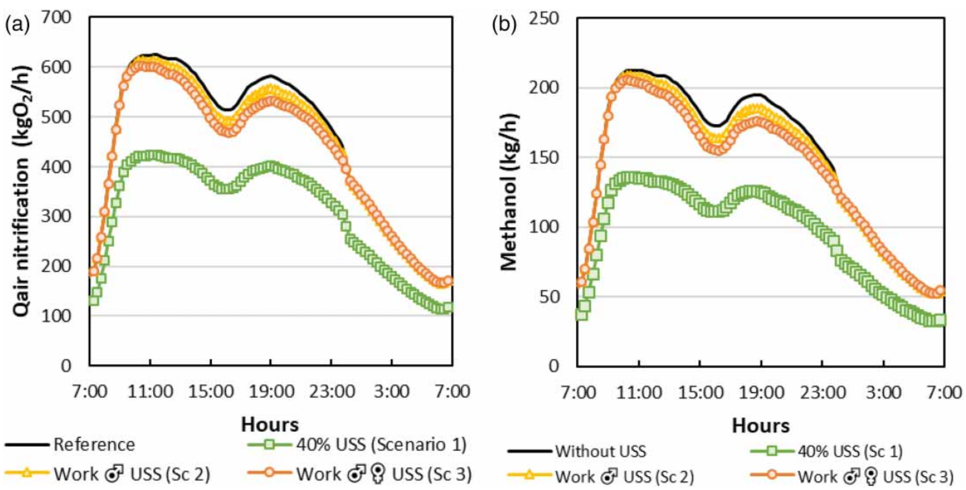

Figure 5 | Daily aeration flow needed at the biofilters to achieve nitrification, (a) and daily methanol dosing required to achieve post denitrification (b) for the reference and the three urine retention scenarios.

These dynamics were calculated for each scenario (1, 2 and 3) using the simulated influent and the operational data collected from MAV plant operators. For scenario 1, the reduction in air flow rate for nitrification was 31.5% and peaked at 32.3%. The reduction rate was less important for scenario 2, which reached 2.5% and peaked at 4.5%, but it was more pronounced for scenario 3, with a maximal reduction in aeration reaching 89.0% (Table 3). The average reduction in methanol consumption at the post-denitrification obtained from scenario 1 reached on average 36.6%, and peaked at 38.2%. Scenario 2 led to 2.3% reduction on average and peaked at 5.1%, whereas for scenario 3 the mean reduction was 4.6% and peaked at 10.2% (Table 3). These results confirm that reduction in aeration and methanol dosing can be achieved proportionally to the level of deployment of USS in relation to the implementation scenario, however, urine source separation at work presents lower reduction rates. Regarding scenarios 2 and 3, the reduction in aeration and methanol were logically observed during work hours, i.e. during the diurnal peak load.

For this calculation, it was assumed that the internal recirculation rate was not modified between aerobic and anoxic biofilters, leading to the same proportion of nitrate that was recirculated to the pre-DN. Due to higher COD:N ratio, more residual COD was degraded aerobically in the biofilter, but this was not detrimental for the overall balance. However, another option would be to increase the internal recirculation to consume more nitrate and COD in pre-DN. The methanol saving would be even more important in that case, but the energy demand for recirculation would increase and should be considered for global evaluation.

3.5. Greenhouse gases balance for the urine collection and treatment

Figure 6 shows the additional GHG emissions linked to the collection and treatment of urine (in positive value), and the benefits (in negative value) of source separation for different urine treatment options. The results are presented for scenario

Table 3 | Simulated overall reduction in aeration flow and methanol consumption in biofilters for nitrification and denitrification, for the three different scenarios for urine source separation compared to reference scenario (without USS)

	Reduction in the aeration flow injected to achieve nitrification			Reduction in methanol addition at the post-Denitrification step		
	Scenario 1(%)	Scenario 2(%)	Scenario 3(%)	Scenario 1(%)	Scenario 2(%)	Scenario 3(%)
Maximum	32.3	4.5	9.0	38.2	5.1	10.2
Average	31.5	2.5	5.1	36.6	2.3	4.6
Minimum	30.8	−0.2	−0.6	35.1	−0.3	−0.8

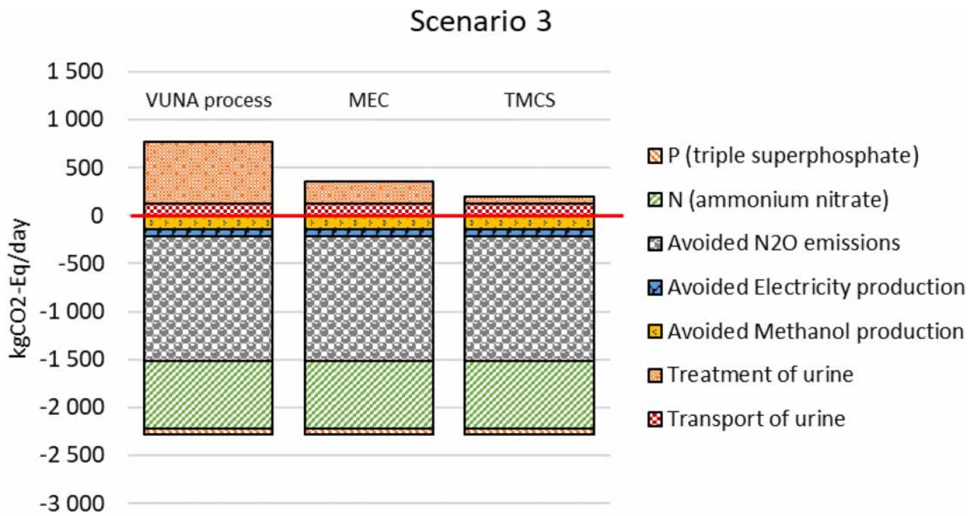

Figure 6 | Comparison of greenhouse gases emissions for the three different treatment technologies (VUNA process, microbial electrolysis cell (MEC), and transmembrane chemisorption (TMCS), for the Scenario 3. Comparison for the two other scenarios is given in supplementary information (Table S4).

3, and similar trends were obtained for scenarios 1 and 2 (presented in Table S4). The main gain relative to global warming potential of the urine source separation scenario is the avoided emissions of nitrous oxide in the WWTP. The estimated avoided N_2O emissions were indeed 1.7 to 6.6 times higher than the additional emissions for urine management in CO_2 equivalent, including energy and chemicals consumption, and nitrous oxide emissions. However, even without the benefits gained from avoided N_2O emissions, urine source separation scenarios were beneficial in terms of global warming potential, since between 250 and 821 $kgCO_2$-Eq would be avoided per day, due to the avoided fertiliser production and the gains obtained at the station (methanol and electricity). This calculation indicates the high benefits of urine source separation on global warming potential, which is especially reinforced in the case of biofilters from which N_2O emissions are relatively high.

It has to be noted that, even with a European electricity mix (0.38659 $kgCO_2$-eq/kWh) and lower emissions of N_2O measured in activated sludge (0.0058 kgN_2O-N/kgN_{in}) (Bollon *et al.* 2013), the urine separation scenarios still presented a beneficial balance for the MEC and TMCS treatment technologies (see Table S5). The avoided production of nitrogen fertiliser is in this case the main contributor to this improvement. In the case of the VUNA process, the avoided emissions do not compensate the emissions from the treatment. The emissions of nitrous oxide in the partial nitrification of VUNA process is slightly larger than the one in the activated sludge process, and the emissions from the avoided fertiliser production is not sufficient to compensate the treatment. Thus, this scenario is more relevant for intensive treatment plant where high nitrous oxide emissions occurr.

4. DISCUSSION

4.1. Implementation strategies and influent modifications

Reduction in nitrogen loads is by default proportional to the level of implementation of urine source separation. Homogeneous implementation in the large urban area of MAV leads to a stable and significant reduction of nitrogen load during the day (from 29 to 31% for 40% urine source separation). In contrast, the specific deployment of USS in office buildings and work areas lead to selective reductions of daily nitrogen peaks. This strategy could potentially help manage the nitrogen peak load at wastewater treatment plants, which is a common problem that most plant operators encounter (Rauch *et al.* 2003; Rossi *et al.* 2009). However, considering the contribution of working area in MAV, the effect remained relatively limited, as only a maximum of 9% reduction was achieved (scenario 3).

Finally, the dynamics of nitrogen loads depend on the catchment size with different intensity of the morning and evening peaks. In small catchment areas, the level of nitrogen load reduction due to USS is slightly more variable than for a larger watershed. For scenario 3, in MAV watershed the reduction load had a standard deviation of 2.3% against 4.3% in the smaller watershed. Finally, even if the benefits of USS implementation in work areas (scenario 2 and 3) would be more interesting in a small watershed, this scenario had a relatively low impact on the shaving morning peak loads.

4.2. Calculated operational benefits for wastewater treatment

Aeration and methanol requirement both decrease in proportion with nitrogen load reduction, i.e. with the increased level of USS implementation. In addition, for the MAV plant, reduction of methanol dosage was more prominent compared to reduction in aeration, firstly because part of the denitrification is performed in the pre-DN biofilter with the influent COD, and secondly because COD:N ratio increased with USS implementation. As a result, to reach the same effluent ammonium concentration, a lower proportion of denitrification would be performed in post-DN with methanol. This phenomenon would be accentuated if the internal recirculation was increased (not considered here), but this would also require more energy to operate the recirculation pumps.

In the case of pre-denitrification, the decrease of nitrate removal leads to a reduction of COD consumption, which would then need to be oxidized in the aerated biofilter. However, COD is also present in urine, thus source separation of urine allows a reduction of COD mass flow and more specifically soluble readily biodegradable COD. Consequently the increase of COD:N is also accompanied by an increase of particulate COD fraction. Such particulate COD is efficiently captured by primary sedimentation and does not reach the biofilters in the MAV plant, and finally less soluble COD would feed the biofilters. Thus, the aeration consumption for COD removal increased slightly with source separation (by 9, 1 and 2% respectively for scenarios 1, 2 and 3), but the calculation of the total aeration demand still showed a decrease by 17% for scenario 1, and by 2 and 4% respectively for scenario 2 and 3.

Despite important reductions that could be accomplished in energy and methanol in wastewater treatment, these savings should be compared to additional requirements for urine management, such as treatment and disposal.

In this study, it was assumed that the separated urine was stored at the building level, collected by trucks and treated at a centralized place (Bisinella de Faria *et al.* 2015, 2020) with three different technologies. Previous researchers used a stochastic model for urine production to investigate the feasibility of combining urine separation with waste sewer design (Rauch *et al.* 2003). In a parallel study, we also evaluated the synergies, which can be found by a combined treatment of urine with rejected liquor from sludge treatment (Besson *et al.* 2021). Another approach focused on collecting the urine in separate tanks, which were equipped with valves that could be controlled remotely. This approach allowed a specific urine release in the sewer network at night to compensate for nitrogen peak loads in the influent wastewater during the morning peak (Rossi *et al.* 2009).

By comparing three different treatment technologies, struvite and TMCS technology presented the lowest greenhouse gas emissions but the use of heat recovered from sludge incineration is beneficial to the technology.

Finally, the carbon footprint balance can be highly positive when all the management chain was considered (Figure 6 and Table S4). It should be noted that only the operational impacts are considered in this case. For considering infrastructure, both the possibilities of limiting the extension of existing plant (benefit) and the construction of new technologies (impacts) could be considered in future work, but this is still highly delicate as no full scale feed-back is available for such realization (Bisinella de Faria *et al.* 2015; Igos *et al.* 2017).

Our previous work showed that 50% urine retention also reduced total phosphorus by 19% (Bisinella de Faria *et al.* 2020). Considering such a reduction, it could also be possible to determine other benefits, like for instance reduction of the coagulant demand. However, this was not considered in this case-study for MAV because mineral coagulant dosage is mainly controlled by physical-chemical capture of suspended solids in primary treatment in the MAV plant.

4.3. Feasibility and future strategies

Implementation of urine source separation at a significant level in a watershed needs to be conducted with an extensive planning for such alternative wastewater management. This is essential for anticipating and financing urine storage, collection and disposal, such as installing toilets and tanks in households, residential buildings or public places. Despite important reductions in energy, chemicals, and carbon footprint that were calculated for global implementation of USS in the entire catchment of MAV (scenario 1), the feasibility of this approach remains challenging.

First from a technical aspect, installing diverting toilets and dry urinals in existing buildings is more difficult than installing these techniques in new buildings under construction (Larsen & Gujer 1996; Larsen *et al.* 2001). The option of installing urine separation preferentially in new buildings should be considered. A driver for urine source separation would be the possibility to avoid a potential expansion of the wastewater treatment plant, thus retrofitting it into a water resource recovery facility (WRRF). Urine source separation could achieve shavings of peak loads without impacting significantly the wastewater flowrate that reaches the WWTP.

From a logistical perspective, it may be more feasible to implement urine separation in office buildings compared to separated residential houses. On average, one toilet is installed in a single house in which 2.2 people live (INSEE *et al.* 2019) whereas the minimal number of toilets in offices is only one toilet for 10 people (*Article R4228-10* n.d.). The option of modifying the toilets in offices and public service buildings seems more realistic, but as demonstrated in this study the effect would be less significant and principally positive for shaving the nitrogen peaks in a small watershed.

Finally, from an economical point of view, the cost of toilet modifications, storage systems, urine transport and treatment installation should also be considered to give a complete vision of the scenarios. Here, it was assumed that treatment of separated urine was realized at a centralized level, which could limit the cost of infrastructures compared to small decentralized installations. Finally, the present work allowed quantifying for a real case-study the environmental outcomes of urine separation scenarios. These results could be possibly translated into cost reductions and money saving in future studies.

5. CONCLUSIONS

Different scenarios of urine source separation (USS) in a specific urban area (Paris catchment of Marne-Aval treatment plant) were simulated. The results of the study are highlighted as follows:

(1) Urine separation reduces nitrogen peak loads on average, and the level of reduction was proportional to the level of deployment in each scenario (household or workplace). Besides nitrogen load, the COD:N ratio changed dynamically which need to be considered for calculating the modification of aeration and methanol dosage.
(2) The dynamic influent generator can be adapted according to the size of the city, and can predict dynamic changes while confirming substantial benefits from specific urine separation during work hours.
(3) The simulated influent profiles allowed quantifying the reduction in energy demand at the biofilters for nitrification and methanol savings at the post denitrification.
(4) A significant benefit in terms of greenhouse gas emissions is demonstrated with the urine diversion strategies, for different recovery technologies, and this was especially due to the high level of N_2O emissions avoided in nitrifying biofilters and nitrogen fertilizer substitution.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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