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ORIGINAL PAPER

Modeling the system dynamics for nutrient removal in an innovative septic tank media filter

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Abstract A next generation septic tank media filter to replace or enhance the current on-site wastewater treatment drainfields was proposed in this study. Unit operation with known treatment efficiencies, flow pattern identification, and system dynamics modeling was cohesively concatenated in order to prove the concept of a newly developed media filter. A multicompartmental model addressing system dynamics and feedbacks based on our assumed microbiological processes accounting for aerobic, anoxic, and anaerobic conditions in the media filter was constructed and calibrated with the aid of in situ measurements and the understanding of the flow patterns. Such a calibrated system dynamics model was then applied for a sensitivity analysis under changing inflow conditions based on the rates of nitrification and denitrification characterized through the field-scale testing. This advancement may contribute to design such a drainfield media filter in household septic tank systems in the future.

Keywords On-site wastewater treatment · Septic tank drainfield · Nutrient removal · System dynamics model

Introduction

According to a recent survey, about 25% of US homes depend on on-site wastewater treatment and disposal systems (OSTDSs) due to the unavailability of a centralized wastewater treatment system [21]. This number is increasing over time ending up in more than 60 million people who had to depend on such decentralized systems in early 2000s in the US [21]. A conventional OSTDS usually includes a septic tank and drainfield which consists of a series of parallel, underground, perforated pipes. This drainfield allows wastewater to percolate into the surrounding soil (the vadose zone). Concentration of ammonium and nitrate in the vadose zone of conventional septic drainfield can be decreased by understanding the physical, chemical, and biological process in a drainfield. Dispersion and diffusion of fluid through solids and adsorption–desorption may be the major physical–chemical process. Biological process involves nitrification and denitrification for nitrogen species. However, systems may create a higher, undesirable level of nutrient loading if improperly designed or managed [14]. Even though properly managed OSTDS can offer several advantages over centralized wastewater treatment facilities, conventional onsite system installations might not be adequate for minimizing nitrate contamination of groundwater, removing nutrient compounds, and attenuating pathogenic organisms [21].

Among currently available OSTDS treatment technologies, passive OSTDS systems are relatively more appealing than the active counterpart because of their consistent nutrient reduction capabilities and relatively low initial and operating costs [3–6, 15, 27]. Passive OSTDS is defined by the Florida Department of Health (FDOH) as a type of onsite sewage treatment and disposal system that excludes the use of aerator pumps and includes no more than one effluent dosing pump with mechanical and moving parts and uses reactive media to assist in nitrogen removal. Reactive media are materials that effluent from a septic

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tank or pretreatment device passes through prior to reaching the groundwater. Some innovative technologies used one or more reactive media to assist in nitrogen removal [20].

Engineered, functionalized, and natural sorption media can be used to treat stormwater runoff, wastewater effluents, groundwater flows, landfill leachate, and sources of drinking water for nutrient removal via physicochemical and microbiological processes [4, 5]. With such functionality, the biofilm can be formed on the surface of soil particles to allow microbes to assimilate nitrogen species although nitrogen cannot be removed by sorption directly. It is indicative that sorption provides an amenable environment for subsequent nitrification and denitrification. In the progress of media development, the media selection and application is no longer only limited to the common natural mineral, such as sand, limestone, expanded clay, zeolite, pumice, bentonite, and oyster shell. The media may also include a variety of industrial and domestic wastes that people used to consider to be. They include but are not limited to sawdust, peat, compost, wheat straw, newspaper, wood chips, wood fibers, mulch, glass, ash, tire crumb, expanded shale, and soy meal hull [4, 5]. Last but not the least, the choice of media mixes depends on the desired length of service, residence time during an operating cycle, and pollutants in the wastewater. In many cases, the constituents to be removed are not only the nutrients but also some other pollutants, such as heavy metals, pathogens, pesticides, and toxins (TCE, PAH, etc.) [4, 5].

The first objective of this study was to review the basic functionality and effectiveness of the newly developed media filter (e.g., a green sorption media filter) with its unique sorption media recipe to remove nutrients, which demonstrates the salient features of such an engineered system to be modeled. The second objective of this study is to conduct a compartmental modeling work using a system dynamics model with respect to the rates of nitrification and denitrification characterized by the collected field-scale dataset. Thus, a system dynamics model produced by STELLA® was applied to further explore the nutrient removal mechanism and sensitivity of the innovative underground media filter in this study.

Materials and methods

System configuration

The wastewater was collected and pumped from the 15-person dormitory at the main campus of University of Central Florida (UCF) to a 3.78 m^3 (1,000 gallon) septic tank. A subsequent dosing tank links the septic tank with the media filter. The single pump and pipe arrangement delivers an average of 0.75 m^3 day^{-1} (200 gpd) wastewater effluents from the septic tank to the media filter for functionality testing in this study during March, 2009 [3–6, 15, 26].

Figure 1 shows the schematic of the media filter with a 60-cm (24 inches)—sand layer on the top of the media filter, which is packed with Astatula sand, a kind of local sand in central Florida. From the left to the right, such a wastewater treatment system starts with a septic tank, an influent distribution system (e.g., a dosing tank), a piping system arranged for dosing the drainfield, and an underground cell including baffled compartments and a riser before the drain section. In the underground cell, the treatment process of the media filter was subdivided into three aerobic/anoxic zones and one anaerobic zone (e.g., marked from section 3 to 6 in Fig. 1). The upper part (i.e., sand part) of the aerobic zones was evenly partitioned into three sections by baffles to support the nitrification. A 30-cm (12 inches)-thick green sorption material mixture layer (designed as anoxic zone in Fig. 1) was placed beneath the aerobic zone. Such artificial zones are exactly our design hypothesis that needs to be verified by using field sampling and analysis.

To enhance the homogeneous treatment and promote the removal efficiency, a specific inlet pipe for dosing [i.e., Plastic Tubing Industries, Inc. (PTI) Multi-Pipe Systems 11 (MPS-11)] was installed for equal distribution of the intermittent influent across the width of the media filter. Besides, some vertical pipes (i.e., oxygenators) inserted in the beginning of the media filter may also introduce air into the designed aerobic zone if needed. Such arrangements of the piping system for correct dosing and venting in concert with the internal partition using baffles and riser in the media filter sustain the essential functionality of these sorption media [6, 24]. It was expected that such a physical

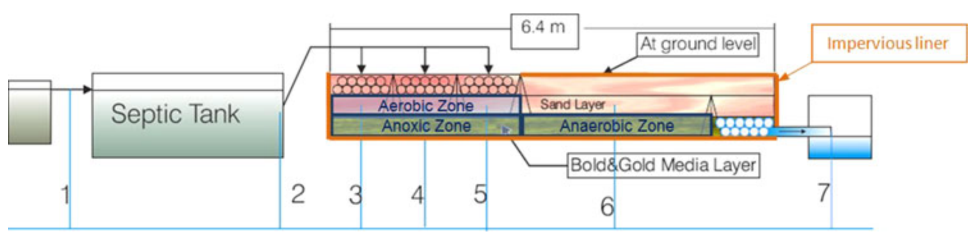

Fig. 1 Schematic of the media filter [6, 24]

setting before the riser and after the baffle where there is a constant flooding zone would foster anaerobic environments to perform the denitrification, whereas the initial venting may maintain a steady aerobic as a preparatory stage. The newly designed media were placed in the flooding zone before the riser as a bottom layer. The sorption material mixes used in this study include approximately 68% fine sand, approximately 25% tire crumb, and approximately 7% sawdust by volume. It has "green" implications because of the inclusion of recycled material as part of the media mixture. This innovative passive underground media filter (i.e., by gravity flow with no pump needed) is highly sustainable, which is designed to fit in any landscape to replace a conventional drainfield, and is highly applicable to a wide variety of septic tank designs [24]. The disposal chamber is prepared for sampling purposes, which allows us to pump the treated effluents back to a nearby sewer line. Albeit the treated effluent still can be polished while percolating down into the vadose zone gradually if there is no sewer line in the neighborhood, in light of all circumstances, the media filter was isolated by an impervious liner from the surrounding soil to keep all nitrification and denitrification processes in such a reactor type filter and avoid any possible groundwater disturbance.

Sampling and analysis

A lab-scaled study was carried out in which sorption isotherm and microcosm tests were used to prove the concept in early stage [28]. From 2009 to 2010, comparative full-scale field testing was established to prove the advantageous features of passive onsite wastewater treatment technologies across several treatment trains at the UCF Test Center [3–6]. In the field campaign, seven process steps and sampling points (marked from section 1 to 7 in Fig. 1) within the media filter system can be identified and shown in Fig. 1 stepwise along the horizontal direction. The media filter was monitored biweekly. Samples were analyzed by Environmental Research and Design, Inc. (ERD), a National Environmental Laboratory Accreditation Conference (NELAC) certified laboratory in Orlando, Florida. In this study, three datasets collected in March 2009 were presented for addressing the water quality conditions and supporting the system dynamics modeling analysis. Dissolved oxygen (DO), pH, and temperature were measured on site using a HACH HQd field case. In addition to those parameters requiring a grab sample analysis mentioned above, ammonia, nitrite–nitrogen (NO_2–N), nitrate–nitrogen (NO_3–N), TN and TP were collected by the team and measured by a certified laboratory (ERD) too.

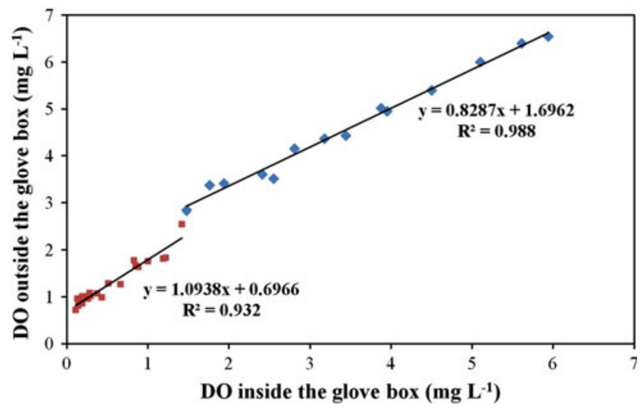

Fig. 2 The relationship between the DO value in the box and that outside the box

All the samples were pumped out of the underground treatment system by a peristaltic pump. The longer it took for sampling, the greater was the chance of oxygen dissolution in outside environment. An imitation experiment was conducted to correct the high DO results. A water sample was put in a glove box filled with nitrogen gas, which mimicked an airtight underground environment. Different amount of nitrogen gas injection into water sample caused different DO readings. When the reading reached the expected value, the water sample was transferred by a peristaltic pump into another container out the glove box. The relationship between the DO value in the box and that outside the box is plotted in Fig. 2. The whole curve is a nonlinear curve. For the reason of simplification, we adopted an approach of piecewise linear approximation. In Fig. 2, the approximation can be made through the use of two piecewise linear functions, in which a greater slope was apparent in association with low DO range. The DO values were calibrated based on these two piecewise linear functions.

System dynamics model

System dynamics modeling, known as a well-established methodology specially for studying and managing complex feedback systems, has been used to address a variety of environmental/ecological studies including environmental impact assessment of coalfields [23], tree growth [19], lake eutrophication assessment [22], wetland study for metals [25], groundwater recharge [1], pesticide control [11], water reallocation [10], wastewater treatment [16], river pollution control [8], lake watershed management [13], lake toxics mass balance assessment [12], and solid waste management [9].

With the aid of a tracer study to prove the concept of the flow patterns providing visualized evidence [7] as to how the flow move through the three compartments as defined

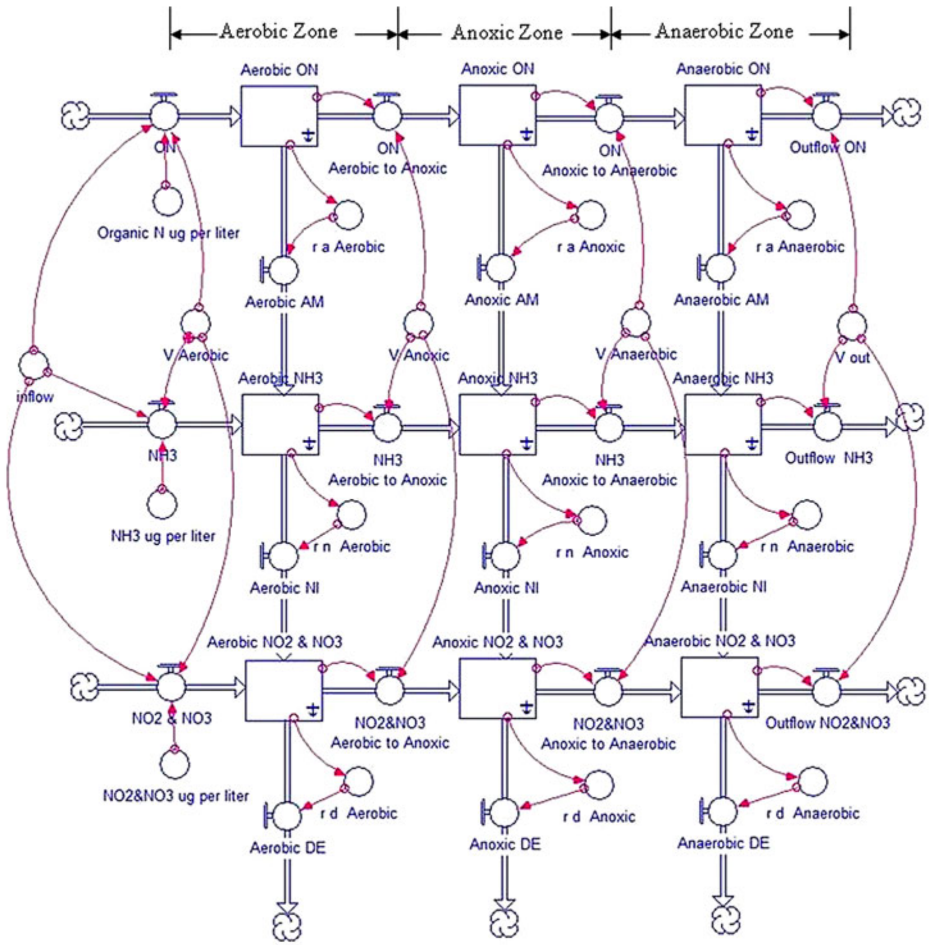

Fig. 3 The stock and flow diagram of nitrogen removal model

Table 1 Description of symbols in stock and flow diagram of aerobic zone in Fig. 3

Symbol	Description
"Aerobic ON"	ON (μg L^{-1}) in aerobic zone;
"Aerobic NH_3"	NH_3 (μg L^{-1}) in aerobic zone;
"Aerobic NO_2 and NO_3"	$NO_2 + NO_3$ (μg L^{-1}) in aerobic zone;
"Aerobic AM"	ammonification (μg L^{-1} day^{-1}) in aerobic zone
"Aerobic NI"	nitrification (μg L^{-1} day^{-1}) in aerobic zone
"Aerobic DE"	denitrification (μg L^{-1} day^{-1}) in aerobic zone
"ON aerobic to anoxic"	ON (μg L^{-1} day^{-1}) transfer from aerobic to anoxic zone
"NH_3 aerobic to anoxic"	NH_3 (μg L^{-1} day^{-1}) transfer from aerobic to anoxic zone
"NO_2 and NO_3 aerobic to anoxic"	$NO_2 + NO_3$ (μg L^{-1} day^{-1}) transfer from aerobic to anoxic zone
"r_a aerobic"	ammonification rate (μg L^{-1} day^{-1}) in aerobic zone
"r_n aerobic"	nitrification rate (μg L^{-1} day^{-1}) in aerobic zone
"r_d aerobic"	denitrification rate (μg L^{-1} day^{-1}) in aerobic zone

in Fig. 1, compartmental modeling work was then applied with respect to the rates of nitrification and denitrification characterized by the collected field-scale dataset. A multicompartmental model based on our assumed flow compartments accounting for aerobic, anoxic, and anaerobic reactive zones in the drainfield filter (see Fig. 1) was then used to fit experimental data to estimate chemical and microbiological metabolic parameters in the context of system dynamics model. Such a model typically has stationary, linear differential equations to describe the time behavior of chemical decay or enrichments in the different pools in terms of rate constants. These rate constants were estimated by fitting the experimental data with the solutions to some of the empirical differential equations. The

Table 2 Description of parameters in the multicompartment model

Parameter	Description	Rate equations	References
k_a	Ammonification constant	$r_a = k_a C_{ON}$	[2]
u_N	Nitrosomonas growth rate	$r_n = \frac{u_N}{Y_N} e^{0.098(T-15)}[1 - 0.833(7.2 - \text{pH})]\left(\frac{C_{AN}}{1+C_{AN}}\right)\left(\frac{C_{DO}}{1.3+C_{DO}}\right)$	[17]
Y_N	Nitrosomonas yield coefficient	$r_n = \frac{u_N}{Y_N} e^{0.098(T-15)}[1 - 0.833(7.2 - \text{pH})]\left(\frac{C_{AN}}{1+C_{AN}}\right)\left(\frac{C_{DO}}{1.3+C_{DO}}\right)$	[17]
K_{20d}	Denitrification rate	$r_d = K_{20d}\theta_d^{(T-20)}$	[18]

Table 3 Experimental data collected in March 2009

Sample sources	Org. N (μg L^{-1})			NH_3 (μg L^{-1})			$NO_2 + NO_3$ (μg L^{-1})		
	4th	18th	31st	4th	18th	31st	4th	18th	31st
Septic effluent	501	752	998	40,137	49,787	49,951	117	55	22
Aerobic zone	745	1,119	804	8,279	11,359	11,331	29,342	42,808	31,322
Anoxic zone	1,396	226	843	13,184	8,996	15,687	5,937	6,691	7,731
Anaerobic zone	308	896	1,061	16,609	13,726	16,638	9	18	8
Removal efficiency (%)	4.4 ± 30.3			65.9 ± 6.9			74.4 ± 15.6		

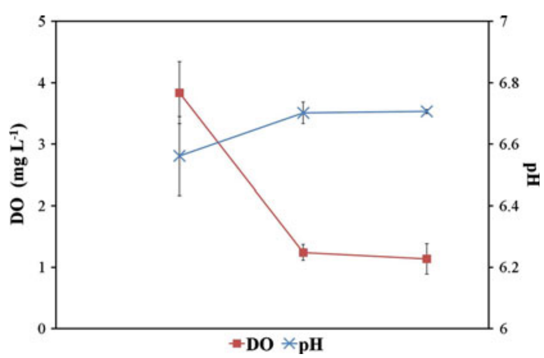

Fig. 4 Tracking of DO and pH along the aerobic (*left* data points), anoxic (*middle* data points) and anaerobic (*right* data points) zones in the media filter system

system dynamics model also has algebraic equations, stemming from material balances on total amounts involving pool masses and the rate constants. In this study, STELLA®, an advanced graphical system programming dynamic software package, was used to develop the mathematical model for the media filter. The stock and flow diagram of nitrogen removal model is presented in Fig. 3. Table 1 summarizes the description of symbols in stock and flow diagram of aerobic zone in Fig. 3. Similar naming rule was also applied to "anoxic" and "anaerobic" zones. Sensitivity analysis was finally performed based on the identified rate constants and possible variability which were used to calculate varying direct nutrient removal under changing inflow conditions. It provides additional information about the robustness of this media filter treatment process.

The following Eqs. 1–3 are used to predict the organic nitrogen (ON), NH_3, and the oxidized nitrogen ($NO_2 + NO_3$). The unit form, μg L^{-1} day^{-1}, was used for all flows and μg L^{-1} for all stocks. Since the stocks have their own outflow to reach a steady-state condition, the value in stock can be read as the "instantaneous concentration" in a unit volume or a point (i.e., sampling port). V is considered as the effective volume (product of volume and porosity) of each zone. dt is the time infinitesimal. In this study, March 2009 was picked up as the experiment period. The description of parameters in the multicompartment model is listed in Table 2, all of which are required to be optimized (i.e., well-fitted) during the model calibration stage.

$$\mathrm{dON}/\mathrm{d}t = \frac{Q_{in}}{V_{in}}\mathrm{ON}_{in} - \frac{Q_{out}}{V_{out}}\mathrm{ON}_{out} - r_a \quad (1)$$

$$\mathrm{dNH_3}/\mathrm{d}t = \frac{Q_{in}}{V_{in}}\mathrm{NH}_{3in} - \frac{Q_{out}}{V_{out}}\mathrm{NH}_{3out} + r_a - r_n \quad (2)$$

$$\mathrm{d}(\mathrm{NO_2} + \mathrm{NO_3})/\mathrm{d}t = \frac{Q_{in}}{V_{in}}(\mathrm{NO_2} + \mathrm{NO_3})_{in} - \frac{Q_{out}}{V_{out}} \times (\mathrm{NO_2} + \mathrm{NO_3})_{out} + r_n - r_d \quad (3)$$

Results and discussion

The performance of media filter

The performance of media filter in regard to both the flow patterns and the removal efficiencies were tested and are

Table 4 Values used in the rate equations of ammonification, nitrification, and denitrification

	Rate equations	Unit	Aerobic zone	Anoxic zone	Anaerobic zone
k_a	$r_a = k_a C_{ON}$	day^{-1}	0.05	0.42	0.23
$\frac{u_N}{y_N}$	$r_n = \frac{u_N}{Y_N} C_T C_{pH} \left(\frac{C_{DO}}{1.3+C_{DO}}\right) C_{AN}$	day^{-1}	3.96	0.32	0.006
K_{20d}	$r_d = K_{20d} \theta_d^{(T-20)} C_{NN}$	day^{-1}	0.26	5.8	9.0
DO	$r_n = \frac{u_N}{Y_N} C_T C_{pH} \left(\frac{C_{DO}}{1.3+C_{DO}}\right) C_{AN}$	mg L^{-1}	4.42	1.33	1.41
pH	$r_n = \frac{u_N}{Y_N} C_T C_{pH} \left(\frac{C_{DO}}{1.3+C_{DO}}\right) C_{AN}$	N/A	6.54	6.70	6.71
T	$r_n = \frac{u_N}{Y_N} C_T C_{pH} \left(\frac{C_{DO}}{1.3+C_{DO}}\right) C_{AN}$	°C	26.4	24.2	23.9

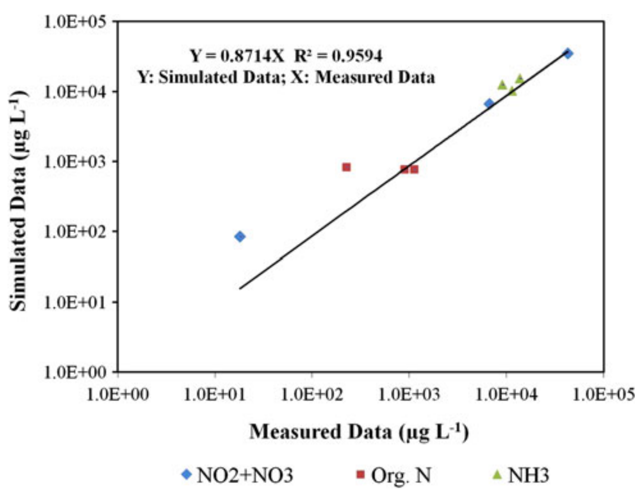

Fig. 5 Correlation between the measured and simulated values in model calibration

presented below. In specific, the results from three sets of data of nitrogen species collected in the media filter in March 2009 are listed in Table 3. It is indicative that both nitrification and denitrification processes occurred in the filter. 65.9% of ammonia and 74.4% of oxidized nitrogen were removed from the septic effluent. There was a trend of low ON concentrations and high ammonia concentrations in septic effluent; then, ammonia concentration dramatically decreased when the wastewater traveled through the aerobic zone. Most of ON had been converted to ammonia through ammonification in the septic tank. The aerobic zone offers a nitrification environment that was successful in oxidizing ammonia. Denitrification process was observed in the anaerobic zone where nitrate concentrations experienced considerable reduction. Besides, the stepped decrease of DO values and the stepped increase of pH values along the pathway in the media filter system proved the theory that denitrification is an oxygen-consuming and alkalinity-producing process (see Fig. 4). It supports expected relationships among the nitrogen species for nitrification and denitrification conditions in such a media filter.

Table 5 Parameter values used for model validation

	Unit	Aerobic zone	Anoxic zone	Anaerobic zone
March 4				
DO	mg L^{-1}	3.54	1.09	0.94
pH	N/A	6.44	6.66	6.70
T	°C	18.4	18.8	18.6
March 31				
DO	mg L^{-1}	3.54	1.30	1.05
pH	N/A	6.70	6.74	6.71
T	°C	25.7	23.4	24.5

System dynamic model

Model calibration

Calibration is the process to find the best match between simulated and observed values. Data collected on March 18, 2009 were used for model calibration. The values of reaction rates and environmental parameters applied in simulation analyses can be seen in Table 4. Runge–Kutta 4 was used as the integration method. The expression of nitrification rate was finally reorganized as Eq. 4. Then the model calibration followed along the direction of nutrient transport from aerobic to anaerobic zone and nitrogen transformation from ON to oxidized nitrogen. The final agreement between the measured and simulated values of ON, ammonia (NH_3), and the sum of nitrite and nitrate ($NO_2 + NO_3$) can be seen in Fig. 5. The slope of the regression line was 0.87 and the coefficient of determination (R^2) was 0.96, both of which support the success of model calibration. The denitrification rate constant in anaerobic zone is 35 times larger than the value in aerobic zone, whereas the nitrification rate is extremely high in aerobic zone. This observation verifies the design hypothesis

$$r_n = \frac{u_N}{Y_N} C_T C_{pH} \left(\frac{C_{DO}}{1.3 + C_{DO}}\right) C_{AN} \tag{4}$$

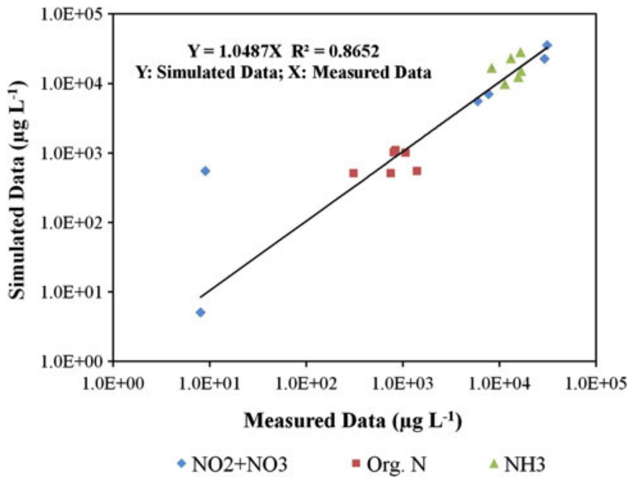

Fig. 6 Correlation between the measured and simulated values in model validation

in which

$$C_T = \begin{cases} e^{0.098(T-15)}, \text{ for } T < 30^{\circ}\text{C}; \\ e^{0.098(30-15)}, \text{ for } T \geq 30^{\circ}\text{C}; \end{cases}$$

$$C_{\mathrm{pH}} = \begin{cases} 1 - 0.833(7.0 - \mathrm{pH}), \text{ for pH} < 7.0; \\ 1, \text{ for pH} < 7.0; \end{cases}$$

Model validation

The other two sets of data collected in March 2009 were used for model validation with the same reaction parameters. Table 5 lists the measured values of the other two sets of data. The correlation between the measured and simulated values is shown in Fig. 6. The slope of the regression line was 1.05 and the coefficient of determination (R^2) was 0.87, both of which show the confirmation of the model validation. Most of points are close to the 45° line except one overrated oxidized nitrogen value.

Sensitivity analysis and model prediction

Since the concentration of nitrogen species in septic tank effluent varies with time, a sensitivity analysis is needed to make a model-based prediction of water quality in drainfield filter effluent reliable. Such sensitivity analysis may further provide improved understanding of how the variation (uncertainty) in the model output can be attributed to the varying nitrogen species concentrations due to the changing model inputs. With the aid of the calibrated and validated system dynamics model, it shows the corresponding ranges of effluent concentrations with ±30% fluctuations of influent nitrogen concentrations on the front of the septic tank system (Table 6). In this sensitivity analysis, the variations of influent ON concentration have the expected direct effect on the effluent ammonia concentration, whereas the influent nitrite and nitrate concentrations do not affect the effluent concentrations as expected. As shown in Table 3 the ammonification rate in anoxic zone is much higher than that in the other two treatment zones. Most of ON in the drainfield filter system starts to be converted to ammonia after traveling through aerobic zone. That is the reason why the variations of influent ON concentration hardly affect the effluent nitrite and nitrate concentrations. However, the variations of influent ammonia concentrations may directly affect both effluent ammonia and $NO_2 + NO_3$ concentrations due to the insufficient HRT and incomplete nitrification in aerobic zone. The remaining ammonia keeps on being converted to $NO_2 + NO_3$ gradually by consuming only a little residual oxygen along the anoxic and anaerobic zones until reaching the outlet of the engineered system. As for the variations of influent $NO_2 + NO_3$ concentrations, since the anaerobic zone has been designed to efficiently treat the low $NO_2 + NO_3$ concentrations always, it would not affect the effluent $NO_2 + NO_3$ concentrations too much.

Conclusions

In this study, the newly developed septic tank media filter for nutrient removal in a field-scale septic tank system was fully tested and presented as an integral part of the passive on-site wastewater treatment technology development. Such a new system was filled with customized green sorption media consisting of recycled products mixed with naturally occurring materials. Overall, 65.9 and 74.4% of ammonia and oxidized nitrogen were removed, respectively. In addition, the system dynamics model was proven useful and effective to improve the design philosophy of

Table 6 The corresponding nutrient ranges of effluent concentrations in model prediction

	Organic N		Ammonia		Oxidized N	
	(−30%)	(+30%)	(−30%)	(+30%)	(−30%)	(+30%)
Organic N	(−1.22%)	(+1.12%)	–	–	–	–
Ammonia	(−30.0%)	(+30.0%)	(−28.8%)	(+28.4%)	–	–
Oxidized N	(0.08%)	(+0.08%)	(−29.9%)	(+29.9%)	(−0.04%)	(+0.01%)

the media filter with specific varying technical settings as well as influent concentrations. Model validation is in good agreement with the data collected from the field-scale testing. Such findings assist in designing a similar type of media filter for better nutrient removal to fit any landscape conditions in the future.

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