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Review

Review of recent advances in alternative septic systems

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ABSTRACT

Conventional septic systems for household waste treatment consist of a septic tank and drain field. This simple technology allows wastes to be disposed of in a manner that minimizes noxious odors, surface contamination, and spread of waterborne diseases. Effluent entering groundwater from septic systems often contains nitrate, phosphate, fecal indicators, and micropollutants such as personal care products, caffeine, pharmaceuticals and hormones. Advanced treatment systems are used in cases where drain fields are not effective due to high water tables or low soil porosity, in densely populated areas, and in environmentally sensitive areas. Examples of improvements to traditional septic systems that are considered to be advanced or alternative technologies include modifications to the tank, the incorporation of filters such as sand filters, the addition of aerobic, anaerobic, and/or electrochemical treatment units, and improvement to drain fields by addition of wood chips and/or other microbial substrates. These modified septic systems are capable of expanding the range of housing sites for which septic systems can provide effective waste treatment, as well as providing more complete removal of contaminants in environmentally sensitive areas.

KEYWORDS: septic systems, advanced treatment systems, drain fields, filters, aerobic-anaerobic, electrochemical.

1. Introduction

Subsurface (on-site, decentralized) sewage treatment systems (SSTSs, septic systems) are an integral part of sewage treatment systems and an important counterpart of the centralized wastewater treatment plant. Historically, household waste has been treated on-site using basic systems such as septic tanks and drain fields. They remain essential today for environmental protection in areas not served by sewer systems. Advanced septic systems may be used to expand the range of environments in which septic systems can provide effective environment protection. In the U.S. alone, household wastewater from 60 million people is treated by on-site septic systems. This varies from about 55 percent of households using septic tanks in Vermont to only about 10 percent in California.

Properly sited septic systems are effective for preventing noxious odors, unsightly surface contamination, and spread of waterborne pathogens. Areas not suitable for septic systems include sites with low porosity soils or high water tables, or in areas of high population density or in close proximity to surface waters. Problems that are encountered by improper siting, operation or maintenance of simple septic systems include contamination of surface and groundwater with nitrogen, phosphorus, and/or human pathogens. Discharge of phosphorus to freshwaters and nitrogen to coastal waters can result in eutrophication, with excessive algae growth and low dissolved oxygen leading to fish kills, toxic blue-green bacteria blooms, and closure of recreational areas. Pathogen contamination of beaches and shellfish areas is also a concern.

Traditional, or simple, septic systems can have poor treatment performance that can result in leaking of minimally treated wastewater into the environment. Biological oxygen demand (BOD) is reduced by

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only about 40% by septic tanks, and if drain fields are poorly sited, designed, or clogged, providing no further filtering or microbial transformations, surface and groundwater can become contaminated. Advanced septic technologies are being introduced to overcome these issues, and expand the range of households for which decentralized treatment is an effective waste treatment option. The present study summarizes recent (2014 to the present) research in advanced septic systems.

2. Background

Conventional septic wastewater treatment technologies, in some cases, are inadequate to meet the current stringent regulatory effluent limits or have frequent failures. Conventional methods for household wastewater treatment include a septic (settling) tank and a drain field.

Septic systems are used for waste treatment in approximately 20 percent of houses in the U.S. (26.1 million). New septic systems added since 2007 (1.54 million) are divided about evenly between rural and suburban areas, with only a small percentage (3%) located in urban areas. Construction and operation permits for new septic systems are provided by local environmental or health departments. A site assessment is performed to determine if soil characteristics, such as porosity, are suitable for proper functioning of the proposed septic system, and appropriated setback distances are established. Possible contamination of water resources by nitrogen and phosphorus may also be considered under some regulatory programs. If the proposed site is unsuitable for a conventional septic system, some states will allow alternative or advanced systems. These approaches typically result in effective design, construction, and operation of household waste treatment systems under laws that govern public health protection and abatement of public nuisances.

3. Conventional septic systems

Conventional septic settling tanks, which are considered a primary treatment unit, are installed in the subsurface. Typically there is a mechanism to access the tank from the surface for periodic removal of solid sludge. Wastewater from the dwelling (e.g. sinks and toilets) flows by gravity into the tank. A baffle or compartment arrangement ensures that the influent does not short-circuit to the effluent. Solid material settles to the bottom of the tank. A vent from the tank, usually through the house, releases gases generated from microbial action to the atmosphere. After about a 24-hour residence time, the liquid and floating oils and grease exit the tank through an overflow line into the drain field, which is a network of perforated pipe. The pipes are generally surrounded by media (e.g. wood chips) and soil, and covered by a geotextile fabric. The solids-free effluent flows through the media and unsaturated soil where the wastewater is treated by absorption and a microbial mat. The drain field is generally located in the upper two feet of surface soil.

Beal *et al.* (2005) reviewed the hydrological and biogeochemical mechanisms important in septic tank drain fields, including soil absorption mechanisms and the causes of hydraulic failure. Inadequate design, insufficiently permeable soils, and clogging can result in hydraulic failure [1]. Incomplete treatment may result from a shallow water table, porous soils, and shallow depth of the unsaturated zone. Nitrate and fecal coliforms are the major septic system effluent contaminants. Models are under development to predict clogging in the biomat zone. Various studies of removal of nutrients and pathogens by soil absorption systems were considered, as well as investigations of water pollution by septic systems. Nitrate contamination of groundwater can be observed in areas without sewers, but the cumulative effects on catchment basin water quality are difficult to determine.

Gunady *et al.* (2015) reviewed the performance of septic systems in Australia [2]. System failure is most commonly due to systems not being situated correctly, such as in areas of low soil permeability or high water table, undersized systems, and poor maintenance. Further management tools are suggested for documenting locations and performances of septic systems, and for providing better training to identify symptoms of system failure.

4. Advanced septic systems

Solid waste in residential wastewater is retained on site by the septic tank. About 40% of the total treatment occurs in the septic tank before discharge to the drain field, where further treatment occurs in the soils around and under the drain field or absorption system. Advanced septic systems or Alternative Treatment Technologies (ATTs) can provide alternative methodologies and/or additional levels of treatment in places where the conventional septic system is ineffective or insufficient. This is most commonly necessary due to insufficient land, poor soil, high groundwater, or proximity to a large body of water. Alternative treatments often produce higher quality effluent than gravity-based septic systems. The types of improvements to traditional septic systems that are considered to be ATTs include modifications to the tank; the incorporation of filters such as sand filters; the addition of aerobic, anaerobic, and/or electrochemical treatment units; and improvement to drain fields by, for example, addition of wood chips and/or other microbial substrates.

4.1. Filters

Treatment systems in which the effluent fecal coliform concentrations are above local regulatory limits may benefit from filtration. These systems can employ sand filters, which consist of a layer of sand, mostly above ground, that wastewater passes through for additional filtration [3]. Sand filters can be used to reduce fecal indicators [4]. Wilcox *et al*. (2009) reported that removal of organic wastewater contaminants such as caffeine, paraxanthine, and acetaminophen, by traditional septic systems is erratic [5]. Sand filtration or aerobic treatment of septic system effluent resulted in contaminant concentrations comparable with full-scale municipal wastewater treatment plant effluents.

Claveaue-Mallet *et al*. (2015) reported on the workings of a modified septic tank with a recirculatory slag filter incorporated to increase phosphorous removal [6]. Recirculation of the septic tank effluent to the second compartment of the septic tank, with a 50% recirculation ratio in the slag filter, was the most effective configuration for phosphorus removal from reconstituted domestic wastewater. Under these operating conditions, the final effluent phosphorus concentrations were 4.2 and 1.9 mg P/L for total phosphorus (TP) and orthophosphate (o-PO_4), respectively, exceeding the target phosphorus concentration of 1 mg P/L.

4.2. Aerobic treatment

Aerobic technologies, such as the activated sludge process, are the predominant methods applied to the treatment of domestic wastewater in centralized collection and treatment systems. This is due to the high rate of organic matter decomposition under aerobic conditions, effective nutrient removal in add-on tertiary systems, and high operational flexibility. Aerobic zones can be added to septic systems by oxygen (air) injection, supporting the growth of fast-growing aerobic bacteria, thereby increasing the rate of soluble organic carbon and solids breakdown. A smaller leach field may be required for aerobic systems than for similar conventional septic systems, allowing septic systems to be employed in areas with limited drainage areas. This can substantially reduce the space required, which can be useful in lots where a large drainage area is unavailable. Aerobic systems generally achieve higher effluent quality than strictly anaerobic systems. This may be important in environmentally sensitive locations, as well as areas with high water tables or other factors that render conventional septic systems impractical.

Abusam *et al*. (2014) reported on the performance of a treatment train consisting of an aerobic bioreactor, a clarifier, and a saturated grass bed for nutrient removal [7]. Ammonia removal exceeded 90%, and total nitrogen was reduced by 81%. Total suspended solids measurements in the effluent from the grass-bed filter indicated that removal rates averaged between 15 and 40%.

Liu and Wang (2017) constructed a simple baffled bioreactor (BBR), operated with an intermittent aeration mode, that effectively removed nearly all nitrogen for small-flow wastewater treatment [8]. The BBR is characterized by an aeration zone, followed by an integrated internal settler, which automatically retains a high biomass concentration of approximately 6 g/L without using a separate sludge return device. Nitrification and denitrification occurred, and approximately 65% of the total phosphorus was removed.

4.3. Anaerobic treatment

Anaerobic wastewater treatment (AnWT), combined with proper post-treatment, can be effective in removing biodegradable organic compounds from wastewater. AnWT can employ technically simple systems, without the expense of air sparging, and are readily adapted to different scales depending on wastewater volume and organic load.

Different flow configurations and solid supports are possible in anaerobic reactors [9-15]. Anil and Neera (2016) determined the effect of vertical baffles in the anaerobic reactor on septic tank performance [16]. The reactor contained copper-modified zeolite as an adsorbent and filter medium for attached microbial growth. The combination of the anaerobic reactor, zeolite filter and disinfection removed 94% of BOD, 99% of total suspended solids (TSS), 46% of ammonia, 31% of nitrate, 48% of total Kjeldahl nitrogen, 71% of phosphates, and 99% of total coliforms. Modern high-rate AnWT-systems, like the up-flow anaerobic sludge blanket (UASB)-process, anaerobic membrane reactors (AnMB), and Anaerobic fluidized Bed Membrane Bioreactor, may offer guidance to designs for on-site wastewater treatment. The main factors dictating the applicability of AnWT are the temperature, the characteristics and concentration of the pollutants, and fluctuations in the waste composition and flow.

Sharma and Kazmi (2015) tested a two-stage system for on-site treatment of domestic wastewater [14]. This system, housed in single cylindrical unit, consisted of two up-flow anaerobic bioreactors and a modified septic tank followed by an up-flow anaerobic filter. The system was started up without inoculation at 24-h hydraulic retention time (HRT). Removal efficiencies of chemical oxygen demand, biochemical oxygen demand, and total suspended solids were 88, 86, and 91%, respectively. Indicator organisms and pathogens were reduced by greater than 90%.

A technology for domestic wastewater treatment being investigated is the anaerobic membrane bioreactor (AnMBR). These reactors are designed to maintain a high mixed liquor suspended solids (MLSS) concentration, resulting in high rates of removal of organics with low sludge production [17]. The up-flow anaerobic sludge blanket (UASB) process is another design for achieving efficient wastewater treatment in the absence of oxygen. UASB reactors have been tested for removal of BOD, chemical oxygen demand (COD), TSS, ammonia, nitrate, phosphate and fecal indicator organisms from wastewater. This technology may be a sustainable treatment option for on-site treatment of household wastewaters.

Tian *et al.* (2014) studied an anaerobic membrane bio-electrochemical reactor (AnMBER) that consisted of an anaerobic membrane bioreactor (AnMBR) equipped with hollow-fiber microfiltration (MF) membranes that served directly as the cathodic chamber of a dual-chamber microbial fuel cell (MFC) [17]. Further developments in AnMBERs may include designs to achieve both nitrification and denitrification by employing intermittent aerobic-anaerobic conditions in the cathodic chamber, instead of completely anaerobic conditions. These hybrid systems rely on both anaerobic and electrochemical microbial reaction mechanisms, and are expected to require further research and development before implementation as on-site waste treatment systems.

4.4. Electrochemical treatment

Electrochemical and fuel cell systems are emerging technologies that produce electricity from wastewater. Yazdi *et al.* (2015) demonstrated an easy-to-operate microbial fuel cell (MFC) stack for septic tanks [18]. This system can be connected in either series or parallel by using pluggable units and a common base for electricity generation from microorganisms during wastewater treatment. Septic tanks are used principally to protect public health and water resources. Energy production, in the form of methane from anaerobic processes or electricity from microbial fuel cells, is unproven as a practical goal for small scale, on-site treatment systems for household wastes.

Phosphorus has been identified as a critical element in eutrophication of freshwaters. Phosphorus removal in SSTSs largely relies on adsorption by soil particles in the leach field, but some soils are not suitable for phosphorus adsorption and have to be periodically maintained or replaced. Lin *et al.* (2017) investigated the feasibility of incorporating microbial electrochemical processes in simulated septic tanks at lab scale (1 L), referred to as microbial electrochemical septic tanks (MESTs), for sewage treatment [19]. Total COD, total P, total N and sulfide removal were monitored. MESTs achieved better P removal (12.2% vs. 77.2%-98.7% at 25 °C, and 7.45% vs. 20.7%-93.9% at 15 °C) than most of the other alternatives. Another electrochemical technique is electro-coagulation, which can be used for removing contaminants from wastewater. Vakil *et al*. (2014) investigated electro-coagulation for treatment of greywater from individual households [20]. Electro-coagulation with aluminum and graphite electrodes, followed by floatation/sedimentation, was capable of removing suspended solids and COD in a stirred tank electro-chemical reactor.

4.5. Denitrifying reactors and drain fields

In conventional septic systems, organic matter is separated and partially degraded in the anaerobic septic tank. Ammonia in the septic tank effluent can subsequently be converted to less toxic nitrate *via* nitrification under aerobic conditions. The nitrate in the effluent then enters the groundwater. In environmentally sensitive areas, it may be necessary to remove nitrate. This can be accomplished *via* microbial denitrification. Facultative bacteria are capable of employing nitrate as a terminal electron acceptor for heterotrophic carbon degradation, resulting in the release of nitrogen as nitrogen gas. This process requires available organic carbon, nitrate, and anoxic conditions. One approach for achieving denitrification is recycling the effluent from the drain field, following conversion of ammonia to nitrate *via* nitrification, to the septic tank, where organic carbon is available and oxygen is absent. Other approaches may employ addition of alternative carbon and energy sources in separate reactors or locations to support denitrification.

Diaz-Elsayed *et al.* (2017) carried out a sustainability analysis of conventional and advanced on-site waste treatment systems (OWTSs) with respect to their ability to remove total nitrogen (TN) [21]. Septic tank and drain field materials were varied for conventional systems, and the advanced systems evaluated consisted of aerobic treatment units (ATUs) and passive nitrogen reduction systems (PNRSs) with nitrification and denitrification stages. Nutrient management of the advanced OWTSs outperformed the conventional systems (96.7-100% vs. 61-65% TN removal), and resulted in phosphorous and nitrogen concentrations less than 40% of the regulatory limits for freshwater (0.06-0.14 vs. 0.37-0.40 kg P-eq/kg TN) and marine eutrophication (0.04-0.06 vs. 0.54-0.65 kg N-eq/kg TN), respectively. The trade-off for nutrient management was higher life-cycle costs.

Lopez-Ponnada *et al*. (2017) reviewed the potential application of wood chips as a source of carbon for denitrification of storm water runoff and effluent from on-site treatment systems [22]. Denitrification technologies for wastewater treatment with wood chips include combined nitrification and denitrification stages, permeable wood chip walls, and wetlands containing wood chips. As much as 80-100% of the applied nitrate can be removed in laboratory experiments, but process performance is difficult to predict due to environment variability and the complexity of lignocellulose degradation. Passive denitrifying wood chip bioreactors have the potential for low operation and maintenance costs during household wastewater treatment, but additional field studies are needed to understand the short and long term effects on nitrogen removal performance of temperature, precipitation, wastewater flow, and inactive periods.

Elemental sulfur particles can also promote denitrification *via* autotrophic sulfur-oxidizing bacteria [23, 24]. In this case, sulfur serves as the energy source for carbon dioxide fixation and nitrate is the terminal electron acceptor under anoxic conditions. De and Toor (2016) constructed a drain field with aerobic-anaerobic (sand-woodchips) and anaerobic (elemental sulfur-oyster shell) media for a septic system to remove nitrogen in the vadose zone and reduce nitrogen contamination of groundwater [3]. Amendment with these electron donors was effective at removing 90% of the total nitrogen. Yang *et al.* (2017) compared micropollutant removal in this system versus a conventional drip dispersal and gravel trench drain field [25]. The micropollutants were monitored in samples from unsaturated soil-water and groundwater from the drain fields and piezometers, and included wastewater markers, hormones, pharmaceuticals and personal care products (PPCPs), a plasticizer, and their transformation products. All three septic systems had similar micropollutant removal efficiencies. Even though contaminants were observed in the groundwater, a human health risk assessment indicated that these pollutants posed little risk to human health. Potential ecotoxicological effects are unknown.

Ammonia and nitrite can also be converted to nitrogen gas by anaerobic ammonia oxidation (ANAMMOX) [26]. In this biological process, nitrite and ammonia are converted directly into nitrogen gas and water. These bacteria are slow growing and strictly anaerobic. The role of the ANAMMOX reaction in conversion of nitrite and ammonia to nitrogen gas in septic systems is unknown as little research on this issue has been performed.

5. Discussion

5.1. Drivers of advanced wastewater treatment

Conventional household waste treatment often consists of a septic tank and drain field. These simple septic systems fulfill the primary objectives of preventing noxious odors and surface contamination of the surrounding environment from household waste disposal. A primary advantage of septic systems over advanced treatment systems is the low operation and maintenance costs due to less operational steps and process monitoring or addition of auxiliary microbial substrates. Advanced septic systems are needed in cases where a conventional septic system cannot achieve these basic functions. This can occur because of local environmental conditions such as high water table, low porosity of soils, and limited land area. In some cases, addition of a sand filter can provide additional filtration and surfaces for microbial growth [5], and oxygen addition can considerably increase the rate of organic matter degradation and nitrification [8].

The septic tank provides for the settling of waste, and some anaerobic degradation of organic matter. The drain field provides filtration and absorption, and depending on air infiltration, aerobic and anaerobic degradation of organic matter, and conversion of ammonia to nitrate by nitrification. Water exiting the drain field and entering the ground water may contain nitrate, phosphorus, and residual organics, including household medications, under normal operational conditions [25, 27]. In environmentally sensitive areas, such as sites in close proximity to surface waters subject to eutrophication, further treatment may be required. Advanced treatments, such as sand filters and aeration, can be effective for removal of residual organics, including household medications [5], and addition of organic matter (e.g. wood chips) can be used to support denitrification for nitrogen removal [3, 22]. Unlike nitrogen, which can be converted to nitrogen gas, phosphorus cannot be converted to a gaseous state. It can only be removed as a component of biomass or sequestered on surfaces, and these could be enhanced or added in advanced treatment system.

Advanced treatment methods can also be used to design, augment, and support drain field functions [28-32]. This may include simple addition of wood chips to increase porosity. Wood chips and other bioactive supports can be used to expand drain field function by providing carbon and/or energy sources for denitrification to remove nitrate from the final effluent [3, 23]. Provision of oxygen in the septic tank, effluent, or drain field can increase aerobic microbial activity, including heterotrophic degradation of organic compounds and nitrification [8]. This can effectively decrease the load of organics on the drain field, increasing both its effectiveness and longevity before clogging. Phosphorus removal could also be increased in the drain field by addition of adsorption surfaces to enhance precipitation in cases where eutrophication of freshwaters is possible.

Previous research has shown that advanced systems can be very effective in achieving desired waste effluent standards. Designs must be based on targeted objectives, in terms of effluent quality, and an understanding of the surrounding soil characteristics, environmental sensitivities, and physical and microbial activities that are encouraged by each of the advanced wastewater treatments [1, 2].

An emerging driver of advanced treatment systems is nutrient and energy recovery [18, 19, 33].

Historically, human waste has been considered a valuable soil amendment for agricultural crops. This has been supplanted by chemical fertilizers, which are easier to apply and pose no threat of disease transmission. Currently, more consideration is being given to possible phosphorous shortages due to exhaustion of existing mines and water shortages due to changes in precipitation patterns caused by global warming. Also, new sources of energy are of importance in developing a sustainable economy and mitigating global warming. Household wastewater can be considered a valuable commodity in this environment, but advanced wastewater treatment systems are required to achieve these returns. Applicable technologies include microbial fuel cells for energy generation, and any number of technologies for decreasing pathogen load in the effluent for local irrigation or other water reuse. These advanced wastewater systems can also be of ultimate value in decreasing the need for expansion of sewer networks and wastewater treatment plant capacity, increasing sustainability, and because they are decentralized, contributing to the resiliency of society's fundamental environmental infrastructure.

5.2. Impediments to advanced systems

Conventional septic systems are often very effective in achieving the goal of preventing noxious odors and unsightly surface contamination. The resulting dispersed plumes of contaminants expected to enter the groundwater from well-operating systems, including nitrate, phosphorous and residual refractory organics (medicines, estrogens, etc.), are not commonly considered to be a threat to human health or the environment [25]. Lusk *et al*. (2017) recently reviewed the fate and transport of nitrogen, phosphorus, pathogens and trace organic compounds from septic systems, and discussed some of the advanced technologies that can be employed to mitigate impacts from these environmental contaminants [27]. Advanced septic systems may incur higher capital, operation, and maintenance costs. Without clear evidence of health or environmental impacts, advanced systems are not expected to be systematically adopted.

Failure of conventional septic standards to achieve even the most basic level of treatment can remain unnoticed. Drain fields can become clogged or ineffective, resulting in short-circuiting, especially during periods of high rainfall [2]. The lack of any systematic monitoring or maintenance to detect or prevent problems discourages upgrades in conventional systems that could improve performance. Similarly, it is very difficult to detect ecosystem impacts of untreated wastewater due to normal septic system performance or failure. Publicly accessible records for locations of on-site septic systems (GPS coordinates), number of households, and age of the systems, combined with records of closings due to indications of fecal coliforms and/or noxious algal blooms, could provide the next generation of data for assessing obvious environmental impacts of conventional septic systems and encouragement of more advanced treatment methods.

Recovery of phosphorous or energy from household waste is not likely to be cost-effective at the local scale. This is due to the low cost of energy and fertilizers, the low amount of power produced by MFCs, and the expense of collection and transportation of waste material. Energy-generation systems employing MFCs increase capital and maintenance costs considerably, due to the initial cost of electrodes and supports and electrode fouling and replacement, respectively. In the current household environment, the power contribution from MFCs would be expected to be minimal.

The true benefits of advanced septic systems may be revealed by techno-economic analyses including capital, operating, and maintenance costs, and comparisons with net-zero buildings [34] and community level decentralized wastewater treatment plants [35]. Simple expenditures, such as addition of a sand filter or an aerobic reaction tank with a small air pump, could considerably improve treatment performance in on-site systems, while at the same time, increasing the longevity of the drain field. Similarly, addition of wood chips to the drain field could increase soil porosity and nitrogen removal, as well as precluding short-circuiting during high rainfall events. Without thorough and flexible techno-economic analyses (TEAs), the merits of advanced treatment systems can be difficult to assess.

6. Conclusion

Conventional septic systems provide a basic level of treatment necessary to prevent nuisance odors and surface contamination.

Failures of septic systems are often overlooked due to lack of maintenance or monitoring.

More field studies on the state of conventional treatment systems, especially with regard to the relationship between performance and longevity, would be helpful in assessing the general need for advanced systems.

Publicly available data on the location, age, and households served by septic systems, combined with reported instances of environmental problems, are needed to establish when advanced treatment systems are warranted.

Simple advanced treatments, such as sand filters and aeration zones, can considerably improve septic system performance in areas with low porosity soils or high water tables.

More advanced systems that support denitrification or phosphorous precipitation may be required for removal of nitrate and phosphorus, respectively, in environmentally sensitive areas.

Nutrient and energy recovery from household wastewater is not likely to be widely adopted due to high capital costs and low product return and value.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

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