Assessing factors affecting the reduction of phosphorus and faecal microbes in wastewater by decentralised wastewater treatment systems

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Abstract

Environmental pollution and risks to human health can result from diffuse sources of pollution originating from decentralised wastewater treatment systems (DWTS). In particular phosphorus pollution can lead to eutrophication and the downgrading of the quality of water bodies, for example, under the Water Framework Directive (WFD) in the EU, and pathogen pollution can result in increased risks of human exposure to pathogens and impacts on industries such as shellfish growing and tourism. The study reported in this paper reviews the effectiveness of various DWTS in removing phosphorus and pathogens from onsite systems. It was found that DWTS are typically not designed to specifically treat these pollutants and the most common type of DWTS, septic tanks, provide only basic treatment. Additional treatment such as filtration-based or wetland systems must be used to achieve desired levels of treatments. The performance of these systems is affected by site specific conditions, such as input load and sources, and climatic conditions and as such operational characteristics and treatment measures must be designed to take account of these factors.

Keywords

Domestic wastewater, pathogen removal, phosphorus removal, septic tanks, wastewater treatment wetland and filtration-based treatment systems

INTRODUCTION

Domestic wastewater is a rich source of many potential environmental pollutants; however phosphorus and pathogens have gained increasing attention in recent decades due to their potential impacts on human health, the environment and important sectors of the economy. High inputs of phosphorus to natural watercourses encourage algal growth that can degrade water quality. For example, the 2013 Water Framework Directive (WFD) classification identified approximately 9% of WFD baseline rivers and 21% of WFD baseline lochs in Scotland as impacted by phosphorus in terms of their chemistry and ecology (O'Keeffe et al. 2015). Both agricultural runoff and small point sources such as decentralised wastewater treatment systems (DWTS) contribute to inputs of phosphorus in surface waters in rural catchments but it has been reported that phosphorus discharges from DWTS, notably septic tanks (ST) may be more readily bioavailable for primary production in receiving waters than phosphorus in agricultural runoff, thereby giving them greater potential to degrade water quality (Stutter et al. 2014). Domestic wastewater is also a source of large numbers of faecal pathogens. Contamination of drinking water, shellfish, bathing waters and aquatic amenity sites by faecal pathogens from diffuse agricultural sources and human sources such as septic tank effluent (STE) increases the likelihood of waterborne illnesses being transmitted to human populations. DWTS discharges have been estimated to contribute approximately 23.5% of the diffuse source *Escherichia coli* (a common indicator for faecal pollution) load or 7.6% of the total load (diffuse and point source) to Scottish groundwaters and surface waters (SNIFFER 2006).

Large numbers of households in rural areas in both developing and developed countries around the world are not connected to mains sewerage systems and therefore rely on the services of DWTS. For example, in rural Scotland approximately 160,000 properties are not connected to centralised sewerage systems and therefore rely on DWTS to treat their wastewater. These DWTS are mainly ST as standalone systems or with post treatment such as constructed wetlands and package systems. When used as sole treatment units, ST have the highest potential for the discharge of phosphorus and faecal pathogens to the environment, aside from direct discharges. The reduction of phosphorus and pathogens by DWTS has typically been of secondary concern in system design, with optimisation of treatment tending usually to focus on removal of solids, organic pollutants and nitrogen.

The research reported in this paper aims to assess the performance of various DWTS in the removal of phosphorus and faecal pollutants from domestic wastewater. The review considers the impact of both traditional and new approaches to onsite treatment on the reduction of phosphorus and pathogens.

RESULTS and DISCUSSION

Sources of phosphorus and removal efficiencies by commonly used DWTS

Sources of phosphorus. The main sources of phosphorus in raw domestic wastewater can be wide ranging. As an example, the source apportionment of phosphorus in raw domestic wastewater in the UK is summarised in Table 1 indicating that the largest sources are human waste and detergents. These estimates can vary depending on water usage as well as diet. Vegetarian households have been shown to produce around half of the amount of phosphorus in their waste compared to households that consume meat (Cordell et al. 2009). The concentrations of total phosphorus in raw domestic wastewater typically range from 13.05 to 25.8 mg l^{-1} for raw wastewater, with an average of about 19.1 mg/l (Lowe et al. 2007).

Table 1. Source apportionment of phosphorus in raw domestic waste water (Defra 2008)

Source	Contribution to phosphorus load
Faeces	23%
Urine	41%
Food waste	5%
Mains supply (phosphate added to reduce Pb in drinking water)	5%
Toothpaste	1%
Dishwasher detergent	7%
Laundry detergent	18%

Phosphorus loading from detergents should currently represent a smaller proportion of total load from households in the EU compared to that shown in Table 1 due to EU bans on phosphates in domestic cleaning products (amendment Regulation (EU) No. 259/2012 of Regulation (EC) No. 648/2004), which places restrictions on the phosphate content of ≤ 0.5 g per standard dosage for domestic laundry from 30 June 2013 and ≤ 0.3 g per standard dosage for dishwasher detergents from January 2017 (European Union 2012). Regulatory limits on phosphate containing detergents have been shown to be effective elsewhere in reducing concentrations in wastewaters and the water environment (Alhajjar et al. 1990, Hoffman and Bishop 1994, US EPA 2002, Foy et al. 2003). Another potentially significant source of phosphorus in domestic wastewater in some countries is the practice of adding orthophosphate to domestic water supplies for the reduction of plumbosolvency in areas where water supplies are still delivered, at least in part, by lead pipework. Average concentrations as high as 1.9 mg l^{-1} have been reported in some areas (UKWIR 2012), which is equivalent to about 20% of the total concentration in the effluent of an average septic tank (May et al. 2010). Only replacement of lead components across distribution networks in many countries would remove the need for phosphorus-dosing in this manner.

Removal of phosphorus. The ability of basic DWTS to removal phosphorus as standalone systems is limited. Although there is considerable variation in the overall levels of phosphorus removal across the range of DWTS, septic tanks as standalone systems typically do not result in significant reductions. Table 2 presents the typical concentrations found in influent and effluent from septic tanks used in a range of configurations.

Table 2. Phosphorus concentrations in effluents of various septic tank (ST) configurations

Raw water (ST influent) TP (mg l^{-1})	STE concentration (mg l^{-1})		System details		Reference
	SRP	TP			
19.1 (13.1-25.8)	-	12.2 (3-39.5)	ST average concentrations based on literature search (n=8 for influent, n=49 for effluent)		Lowe et al. 2007
13.3[a]	-	7.07[b] 0.22[c]	ST plus filter bed system, results for 4 of the systems tested		Jenssen et al. 2010
6.6		5.5 0.04			
26.8		24.0 1.22			
18.2		14.0 0.02			
-	1.9	3.3	Old ST; no soil adsorption bed, results for field drain discharge including STE; ave. from one year.		Ockenden et al. 2014
-	1.4	1.9	Old ST supplemented with modern tank. Results for field drain discharge, including STE ave. from one year.		Ockenden et al. 2014
-	4.8 (0.3-10.6)	9.1 (4.5-18.0)	Median concentrations from four STs		Brownlie et al. 2014
-	8.8 (2.3-11.9)	11.9 (5.8-14.4)	ST with mechanical mixing. Median concentrations from one ST over four month monitoring period		Brownlie et al. 2014
-	5.5 (1.4-10.6)	9.3 (1.9-14.4)	ST with chemical dosing and tank with aeration and filter system. Median concentrations from two STs over four months		Brownlie et al. 2014
-	11.6	15.0	ST (concrete)	Sampled STs chosen from a range of locations across England	May et al. 2014
	14.5	18.4	ST (brick)		
	9.4	17.4	ST (concrete)		
	13.4	15.0	ST (brick)		
	10.7	12.9	Klargester® PTP		

SRP: Soluble reactive phosphorus; TP: Total phosphorus; PTP: Package treatment plant (incorporating oxygen transfer) [a] septic tank effluent; [b] outlet of biofilter; [c] outlet of filter bed.

The literature suggests that significant reductions are typically only achieved with additional treatments. Many phosphorus removal mechanisms have been designed as retrofit measures as septic tank operation alone is insufficient, where phosphorus pollution is a concern. Operational conditions may be altered to enhance removal (chemical dosing to enhance sedimentation, post-sedimentation treatment such as aeration, coagulation and flocculation to enhance removal by filtration/adsorption), however the types of processes and filtration or adsorption media utilised will determine the overall efficiency of the removal. Physical, chemical and biological processes are all important to removal, but particularly sorption (Kõiv et al. 2009). Filters are thus used as part of DWTSs when space allows. Such systems include filter beds (Jenssen et al. 2010, Nilsson et al. 2013a) and/or sub surface flow constructed wetlands (SSF CW) (Mæhlum and Stålnacke 1999, Kõiv et al. 2009). Filters provide large phosphorus adsorbing areas, typically long retention time, diverse microbiological populations and flexibility in alternating aerobic-anaerobic zones (Kõiv et al. 2009). Vohla et al. (2011) reviewed a large body of literature evaluating the phosphorus-removal properties of various filter media (natural materials, industrial by-products and man-made products), with the performance of materials used in full-scale plants shown in Table 3.

Table 3 Examples of phosphorus removal efficiency by different filter materials in constructed wetland systems (adapted from Vohla et al. 2011).

Material	Study type	P treatment efficiency
Gravel	Three gravel based CWs, 2° effluent, 2 years	P removal -40% to 40%; range of adsorption capacity
	Full-scale CW, VSSF planted gravel filter	PO_4^{3-}-P removal efficiency 4.33%
Limestone	Meso-scale experimental CW received effluent from a treatment wetland for 19 months	TP removal 46%
	Full-scale CW (SSF wetland cell treating wastewater from dairy farm, 1.5 years)	P removal on average 4.3%, mean reduction 14.5%
Marl gravel	Full-scale CW, Filter treating swine wastewater after anaerobic lagoon treatment	TP removal 37-52%
Peat	Small-scale CW in field (landfill leachate from activated sludge plant and bio-pond)	TP removal: 77% from sludge water, 93% from bio-pond water (at 6 mo.)
Sand	Full-scale CW, HSSF sand filter	P in soil after 8 yr: 0.117 g P kg^{-1}, removal 72%
	Full-scale CW, HSSF sand filter	P in sand after 5 yr: 52.8 mg kg^{-1}, removal 78.4%
Shellsand	Meso-scale CW in field, HSSF filter in greenhouse for household	335 g P kg^{-1}, saturated before 2 yrs,
Wollastonite tailings	Full-scale CW SSF wetland cell (wastewater from dairy farm)	Soluble P removal 12.8%, mean reduction: 27.5%
Fly ash	Full-scale CW, three stage system, one filled with fly ash	Majority of TP absorbed by fly ash, TP removal about 83%
Blast furnace slag (BFS)	Small-scale CW (dairy farm wastewater, seven months.)	P removal 72%
	Full-scale CW (seven months)	TP removal up to 99%
	Full-scale CW VSSF reed bed, granulated BFS	Average TP removal 45%
Filtralite-P®	Small, meso and full-scale CW	Extracted P (mg P kg^{-1}): 3887 (small), 4500 (meso), 52 (full)
	Full-scale CW, upflow filter 3 years	P removal 99.4%
Leca (Estonian)	Full-scale CW, VSSF + HSSF filter bed, 2 years	TP removal 89%
LWA(Norsk Leca)	Full-scale CW (wastewater from households, 4 years)	>95%
Norlite	Full-scale SSF CW cell, dairy wastewater	P removal 34%

CW: Constructed wetland; VSSF: Vertical subsurface flow; HSSF: Horizontal subsurface flow; SSF: Subsurface flow; P: Phosphorus; TP: Total phosphorus; PO_4^3: Othophosphate

The review by Vohla et al (2011) demonstrated the wide variation in performance for various materials, with sand and peat demonstrating the best performance for natural filter media. Higher performance for some industrial by-products (blast furnace slag) has been reported; however efficiency depends on the configuration of the system and source of the slag. Man-made products have been found to show high retention potential, with most materials having a pH above 7.0 and high calcium or calcium oxide content thus suggesting retention by precipitation. Other factors such as filter media particle size, hydraulic retention time and rates of organic load may affect overall performance (Jenssen et al. 2010, Nilsson et al. 2013a, Nilsson et al. 2013b). Using a pre-treatment filter (e.g. a vertical flow pre-treatment system) to reduce the amount of organic material in wastewater may improve the efficiency of filter beds and SSF CW in terms of phosphorus removal (Mæhlum and Stålnacke 1999, Nilsson et al. 2013a). Filter media can lose their phosphorus-sorption capacity over time as it becomes saturated (Patterson 2001, Duenas et al. 2007, Jenssen et al. 2010, Vohla et al. 2011) but this may vary based on wastewater strength and nature of the materials. Materials such as Filtralite-P®, opoka and dehydrated oil shale ash appear to be very promising however may require additional testing to determine efficiency over time, and more application on large scale plants (Vohla et al. 2011). Mineral-based sorbents can be easily replaced and potentially reused as agricultural fertiliser (Nilsson et al. 2013b), which is particularly important as global resources of phosphorus are diminishing (Cordell and White 2011).

A comparison of the treatment efficiencies of various DWTS is summarised in Table 4. Some package treatment plants (PTPs) show improved results on traditional septic tanks, however significant removals only appear to be achieved with combination systems that allow for settlement, and filtration (CW plus filter) depending on operational features, local conditions and wastewater strength.

Table 4. Total Phosphorus (TP) removal efficiencies of various DWTS

DWTS type	% TP reduction in wastewaters	Reference
Soil filter beds (aged 14 – 22 years)	12	Eveborn et al. 2012
One-chambered ST	29.3	Nasr and Mikhaeil 2013
Three-chambered ST	33.1	Nasr and Mikhaeil 2013
Sequencing batch reactor (SBR) package treatment plant (PTP)	87.5	Akunna and Jefferies 2000
Klargester (PTP)	47.6	Kingspan Environmental 2010
Constructed wetland (CW)	Year 1: 20 Year 10: 10	Duenas et al. 2007
CW (during the first year)	60	Ockenden et al. 2014
ST plus subsurface flow CW (planted)	95.7-98.3	Chang et al. 2011
ST plus subsurface flow CW (un-planted)	85.7	Chang et al. 2011
ST plus two-step vertical flow CW	71.4	Nguyen et al. 2007
ST plus sand filter bed	almost 100	Robertson 2012
ST plus peat filter	Year 1: 50 Year 12: 26.6	Patterson 2001
ST plus filter bed systems (biofilter (LWA) and media filter bed (Filtralite P®)	> 94	Jenssen et al. 2010

Sources pathogens and treatment efficiencies of commonly used DWTS

Sources of pathogens: Pathogens in wastewaters are generally derived from the guts and faeces of warm blooded animals. Hence, their occurrence in natural waters are usually from point sources such as failing cesspools, animal derived sources such as feedlots, dairy farms or intensive animal husbandry, and human derived sources such as sewage works, combined sewer overflows or septic tank effluent (STE) (Macler and Merkle 2000). Human and livestock wastes can contain pathogens, including bacteria (e.g. *Salmonella spp., Vibrio cholera, Shigella spp, Escherichia coli* (*E. coli*), and coliforms), viruses (e.g. Adenoviruses, Noroviruses, Hepatitis A, Echnoviruses and Coxackieviruses), protozoa (e.g. *Cryptosporidium spp.*, *Giardia spp.)* and helminths (Malham et al. 2014). The literature on pathogen removal by DWTS focuses mainly on a limited number of bacterial groups of interest, typically faecal and total coliforms (FC and TC), *E. coli* and intestinal enterococci.

Removal of pathogens. Concentrations of pathogens in DWTS effluent may show a higher level of variability than centralised treatment works due to variations in household water use and wastewater production on a local scale. Table 5 summarises reported pathogen levels in raw wastewater and STE. The table suggests that the processes occurring in septic tanks (which include mainly settlement in sludges and other processes such as predation by protozoa, natural die off, adsorption onto particles and flocculation) provide only limited removal of faecal pathogens, in the order of 1 to 2 log reduction.

Table 5. Mean pathogen concentrations in raw wastewater and septic tank effluent (STE)

Parameter	Mean concentration in raw wastewater (cfu 100 ml^{-1})	Mean concentration in STE (cfu 100 ml^{-1})	Reference
Total coliforms	3.9×10^7	2.5×10^7	Kay et al. 2008 (UK)
	-	7×10^9	Gill et al. 2007 (Ireland)
	$2.0\text{-}3.5 \times 10^8$		Kadam et el. 2008 (India)
	9.55×10^7	5.98×10^7	Mbuligwe 2005 (Tanzania)
Faecal coliforms	1.2×10^8	-	Harrison et al. 2000 (USA)
	$2.0\text{-}8.0 \times 10^7$	-	Kadam et el. 2008 (India)
	1.7×10^7	7.2×10^6	Kay et al. 2008 (UK)
	-	2.9×10^5	Pundsack et al. 2001 (USA)
	4.26×10^7	2.53×10^6	Mbuligwe 2005 (Tanzania)
Enterococci	1.9×10^6	9.3×10^5	Kay et al. 2008 (UK)
	4.0×10^5	-	Blanch et al. 2003 (Sweden)
	1.0×10^6	-	Blanch et al. 2003 (Spain)
	1.3×10^6	-	Blanch et al. 2003 (UK)
E. coli	$1.2\text{-}3.3 \times 10^6$	-	Kadam et el. 2008 (India)
	-	5.0×10^6	Gill et al. 2007 (Ireland)

Where aerobic biological degradation is part of a DWTS treatment regime, treatment may not be significant due to the enhanced role of the microorganism in the biological treatment processes. However, where anaerobic processes are part of the treatment processes (e.g. in septic tanks operating in tropical climate) there may be a general reduction in pathogens due to die off of some organisms in oxygen-deficient conditions. Table 6 summarises the reported performances of various DWTS in pathogen removal. Where a DWTS consists of mainly sedimentation (e.g. septic tanks), the level of pathogen reduction may be limited. Thus combining the DWTS with biological processes (e.g. constructed wetlands or package treatment plants equipped with oxygen transfer facilities), and processes that enhance predation, desiccation, ultra violet radiation (high in tropical climate) and filtration through soil and vegetation can further enhance the effectiveness of the systems in pathogen removal.

Soil filtration reduces pathogen transport through filtration and adsorption but can be affected by the properties of drain fields including the soil type, texture, presence of organic matter and the formation and maintenance of a biofilm (Harrison et al. 2000, Stevik et al. 2004, Pang et al. 2003), which can limit the efficiency of drainfields to retain pathogens (Beal et al. 2006, O'Luanaigh et al. 2009, O'Luanaigh et al. 2012, Gill et al. 2007, Stevik et al. 2004). Adsorption can be influenced by hydraulic loading, ionic strength, pH, and surface particle of charges (Stevik et al. 2004). Rainfall can impact a number of these properties and thus influences the retention of pathogens in the drainfield, potentially causing desorption and remobilisation of pathogens (Arnade 1999 Pundsack et al. 2001, Stevik et al. 2004, Chen and Walker 2007, Okoh et al. 2010).

CONCLUSIONS

Source control measures, such as regulatory limits on phosphate containing detergents, have been shown to be effective in reducing phosphorus concentrations discharged to the environment however there is a limit to the level of impact these measures can have, and source control options for reducing pathogens are impractical. Furthermore, septic tanks, which are the most common DWTS, have also been shown to be capable of providing only a limited level of treatment for the removal of phosphorus and pathogens from domestic wastewaters. Modern package treatment plants can provide some improvements for phosphorus removal compared to traditional septic tanks, however, their performance is dependent on the type of package plant and post treatment provisions. Additional post septic tank treatments are thus required where the reduction of phosphorus or pathogens is required. Filtration-based treatment systems may be effective; but their efficiency depends upon the type of filter media and their configuration. Sand, peat and alternative media filters have demonstrated good results for both phosphorus and pathogen removal. The performance has been found to reduce over time, and thus will require regular maintenance to ensure effective treatment. The performance of the filtration-based systems also depends on the type of treatment system and climatic conditions. Constructed wetland systems, including those that incorporate filter media, show good performance for the removal of both pollutants, however, site specific conditions such as temperature, rainfall, and properties of the source wastewater may all affect their performance.

It has also been found that the most effective measures for phosphorus and pathogen reduction from septic tank effluents are those measures that maximise solids reduction and also encourage favourable conditions for biological processes and microbial die off. For effective reduction of both phosphorus and pathogens, DWTS need to be designed to production characteristics, as well as to site specific conditions, which include consideration of input loads (e.g. use of detergents, use of phosphorus for plumbosolvency), system operational characteristics (e.g. avoiding hydraulic overload) and post-sedimentation measures (e.g. aeration facilities, use of constructed wetlands systems, and filtration and infiltration systems).

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Table 6. Mean bacterial concentrations within wastewater effluent after treatment (cfu 100 ml^{-1}) and mean removal rates reported (%)

	Total coliforms		Faecal coliforms		*E. coli*		Enterococci		Reference
Treatment type	Effluent conc.	Removal %	Effluent conc.	Removal %	Effluent conc.	Removal %	Effluent conc.	Removal %	
ST only	5.98×10^{7}	37.40%	2.53×10^{7}	40.17%	-	-	-	-	Mbuligwe 2005
ST plus soil drainage field	-	-	-	90%	-	85%	-	-	Tomaras et al. 2009
	-	-	1.60×10^{6} – 1.6×10^{7}	82.0-98.6%	-	-	-	-	Harrison et al. 2000
Constructed soil filter (treating domestic and STE)	1.5×10^{5} - 3.6×10^{5}	99.80-99.93%	3.1×10^{4} – 8.3×10^{4}	99.56-99.92%	1.5×10^{4} - 2.4×10^{4}	98.91-99.95%	-	-	Kadam et al. 2008
ST plus sand filter	-	-	4.2×10^{4} – 1.8×10^{5}	99.4-99.96%	-	-	-	-	Harrison et al. 2000
	-	-	(35-60)^{a} (110-220) ^{b}	99.986-99.992%^{a} 99.93-99.96%^{b}	-	-	-	-	Pundsack et al. 2001
ST plus peat filter	-	-	6^{a} 4-5^{b}	99.997%^{a} 99.9984-99.9987%^{b}	-	-	-	-	Pundsack et al. 2001
	-	-	<200(initial) 650 (12 mo) 1650 (6 yr) 3200 (13 yr)	>99.96% 99.90% 99.70% 99.50%	-		-	-	Patterson 1999^{c}
	-	-	-	-	2.7×10^{3} - 1.2×10^{4}	97.60-99.95%	-	-	Gill et al. 2007
ST plus CW	-	99.50%	-	-	-	99%	-	-	O'Luanaigh et al. 2009 (reed bed)
	-	-	400-500^{a} 5900-7100^{b}	99.87^{a} 99.83^{b}	-	-	-	-	Pundsack et al. 2001 (cattails and bulrush)
	4.5×10^{3}	>99.99%	3×10^{3}	>99.99%	-	-	-	-	Mbuligwe 2005 (engineered CW)
Subsurface upflow CW plus filter media (treating STE)	-	-	71-1738	97.06-99.98	<1-63	99.80 - 100%.	-	-	Chang et al. 2011
ST plus biofilter (LWA) plus media filter (LWA-Filtralite-P®)	-	-	0-<3	-	0	-	<10 to <300	-	Jenssen et al. 2010

[a] Summer; [b] Winter; [c] Performance over 13 years operation; cfu: Colony forming units; ST: Septic tank; CW: Constructed wetland; LWA: Light weight aggregate

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