Environmental Science
Water Research & Technology

PERSPECTIVE

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Environ. Sci.: Water Res. Technol.*, 2025, **11**, 1621

Emerging investigator series: are we undervaluing septage? Rethinking septage management for nutrient recovery and environmental protection

Kevin D. Orner, †*[a] Lewis S. Rowles, †[b] Sara Heger [c] and Ben Howard[d]

Received 6th December 2024,
Accepted 2nd April 2025

DOI: 10.1039/d4ew00998c

rsc.li/es-water

An estimated 20–25% percent of households in the US rely on on-site sanitation *via* septic tanks to manage their wastewater. Septage management strategies such as land application, treatment at wastewater treatment plants, and treatment at independent septage treatment plants are common regulated and protective processes for managing septage. There can, however, be potentially negative environmental impacts such as groundwater contamination if septic systems are failing or improperly designed. In this perspective, we reimagine septage management at each step of the septage value chain, identify barriers to change, and propose solutions to overcome these existing barriers. Reimagined septage management can take both high-level and context-specific approaches, including upgrading or retrofitting older septic takes to be impermeable and promoting proper tank pumping intervals, short transport distances, resource recovery, and safe reuse. These solutions could improve economic, environmental, and social sustainability over the status quo. Barriers such as lack of comprehensive data, aspects of decentralized regulation and management, public perception, and impacts of climate change can be overcome *via* policy best practices, increased stakeholder engagement, improved data collection, integration of machine learning, and climate change adaptation.

Water impact

Septage is an untapped waste stream that could be utilized for resource recovery and for its potential economic, environmental, and social benefits. Reimagined septage management could promote recovery of beneficial nutrients, energy, and water. The industry should strive to overcome existing barriers *via* policy best practices, increased stakeholder engagement, improved data collection, integration of machine learning, and climate change adaptation.

1. Introduction

Over 30 million households in the US are estimated to rely upon on-site sanitation *via* septic systems to manage their wastewater, with distribution varying by state (Fig. 1).[1] Septic systems typically consist of a tank that produces septage followed by soil treatment. However, the decentralized nature of septage management means that accurate quantities and management pathways across regions and the country are largely unknown. The septage from these septic tanks needs to be periodically removed, treated, and disposed.[2] Septage

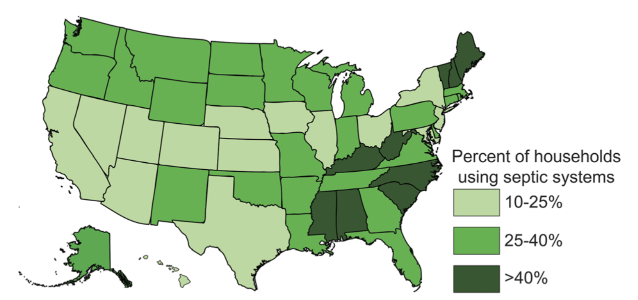

Fig. 1 US Census 1990 – percent of households using septic systems by state, illustrating the wide variability in septic system usage across the United States and highlighting the potential for geographic nutrient recovery and environmental protection through improved septage management practices.[3]

[a] *Wadsworth Department of Civil and Environmental Engineering, West Virginia University, Morgantown, WV 26506, USA. E-mail: kevin.orner@mail.wvu.edu*
[b] *Department of Civil Engineering and Construction, Georgia Southern University, Statesboro, GA 30460, USA*
[c] *Water Resources Center, Onsite Sewage Treatment Program, University of Minnesota, St. Paul, MN 55108, USA*
[d] *Great Lakes Community Action Partnership - Rural Community Assistance Partnership, Athens, OH 45701, USA*
† Co-first authors.

has the potential to be a large-scale feedstock for resource recovery. Given the uncertainty of septage mass and the multitude of both established and emerging septage management technologies available, navigating septage treatment and disposal options and considering resource recovery can be a complex challenge for local decision makers.

Common septage management strategies include land application, treatment at wastewater treatment plants, treatment at independent septage treatment plants, and disposal at a landfill. All states are subject to federal regulations (40 CFR part 503) for biosolid use and disposal. States have the authority to make independent decisions while complying with the rule. Local or tribal and territorial governments can also further regulate biosolid use and disposal. The first strategy, land application, has the benefits of low capital as well as operation and maintenance costs, but requires available land.[4–7] Septage can be applied to the land surface, incorporated into the subsurface, or buried. Concerns over limitations of land application have been raised in communities and state organizations. Some local health authorities are facing staffing constraints that impede their capacity to supervise correct application practices and address odor complaints. The second strategy, treatment at a wastewater treatment facility, has moderate costs and is common for medium- to large-sized communities. The facility regulates the use of the systems and facilities can allow septage to be added to an upstream sewer manhole, at the plant headworks, or at the sludge handling process. These facilities have varying levels of resource recovery. The third common septage management strategy, treatment at an independent facility, has high costs and is often the last resort if no land or wastewater treatment facility capacity is available. These facilities frequently utilize drying beds with the dewatered septage landfilled or land applied.

Conventional septage management methods often have limited economic benefits and can raise environmental concerns depending on the level of resource recovery such as electricity, fertilizer, and water. Viable business opportunities potentially exist for products generated from septage *via* resource recovery technologies. States may wish to consider promoting policies that transition away from practices like landfilling and land application. Septage could be a viable feedstock for anaerobic co-digestion and address organic waste diversion challenges.[8] For example, to meet the 2025 goal of 75% organic waste diversion from landfills in Senate Bill 1383 in California, CalRecycle estimates that new infrastructure is needed to increase digester capacity from 1.1 million tons to 5.1 million tons per year of organic waste. Meeting the 2025 goal with anaerobic digestion infrastructure would increase biomethane production to approximately 400 million cubic meters; the biomethane could be used to produce over 200 MW of electricity and 28 million diesel gallon equivalents of transportation fuel each year.[9]

2. Environmental concerns with current practices

Septic systems face challenges due to climate change impacts and suboptimal practices in installation, operation, and maintenance. The infrequent pumping of septic tanks (the timing of which is often context-specific) can pose significant environmental risks.[10] This practice often leads to accumulation of solids and fats, oils, and grease (FOG) in the tank, which can eventually enter the soil treatment area, compromising its effectiveness. When solids and FOG enter the soil treatment area, they can cause excessive biomat growth, reducing the system's ability to treat wastewater effectively. This clogging can result in hydraulic failure, where wastewater backs up or surfaces above ground, creating direct pathways for untreated sewage to come in contact with humans and contaminate surface waters.[11] Failing and poorly designed septic systems, particularly in areas with high system density or vulnerable environmental conditions such as high water tables or highly permeable soils, can release unsafe levels of pathogens, nutrients, and other contaminants into groundwater and nearby surface waters.[12,13] Low-income communities face disproportionate risks from septic system contamination as unincorporated areas with higher poverty rates typically rely more heavily on these systems than incorporated communities.[14] In coastal areas, the release of excess nutrients from failing septic systems has been linked to harmful algal blooms and degradation of aquatic ecosystems.[15] For example, Murphy *et al.* found that septic system density and rainfall events were significant predictors of human fecal contamination in private wells.[12]

Climate change is exacerbating the environmental risks associated with septic systems, especially in coastal regions. Rising groundwater tables, more frequent flooding, and sea level rise can compromise system performance by reducing vertical separation distances and increase the likelihood of failure.[16] Specifically, coastal septic systems haven shown diminished performance under climate change scenarios, with increased risk of groundwater contamination and system inundation.[17–20] Compound flooding events, where multiple flood drivers like storm surge and heavy precipitation occur simultaneously, pose a growing threat to coastal septic systems.[21] These events can overwhelm systems, leading to increased contaminant release and potential public health hazards. While proper septage management is crucial for addressing environmental concerns, it's important to note that septage management alone cannot improve or fix a failing septic system, underscoring the need for a comprehensive approach that includes both septage management and proactive system maintenance or replacement.

Beyond these immediate environmental risks, wastewater treatment operations can contribute to climate change through greenhouse gas emissions. Specifically, septic systems produce methane and nitrous oxide, both potent greenhouse gasses, as a result of anaerobic decomposition processes.[22] It has been estimated that septic tank emissions account for approximately 0.5% of total *per capita* emissions in the US.[22,23] The climate impact of septic systems is not fully understood. Total emissions numbers are compounded by the energy requirements for pumping and maintenance activities. However, it should be noted that while septic systems require less energy to operate than centralized wastewater treatment plants, they may produce proportionally more methane emissions per volume of wastewater treated, highlighting the complex trade-offs involved in wastewater management decisions.[22,23]

3. Reimagining septage management

The potential impact of resource recovery from septage is promising. Given an estimated 5.5 billion gallons of annual septage is produced (*i.e.*, 220 gallons per household), septage management can be reimagined to produce improved economic, environmental, and social benefits.[2] Septage contains disease-causing pathogens as well as concentrated nutrients that can negatively impact the environment (*e.g.*, algal blooms) if not properly handled and processed. Instead of thinking of septage as a waste to be discarded, septage can be reimagined as a beneficial and plentiful resource. The mass of nutrients in septage can be estimated by multiplying the volume of septage by the septage's nutrient concentration. This nutrient concentration varies in reality based on the type of septic tank used, water supply, pump-out frequency, climate, geography, and household water habits.[2] Given that septage contains about 600 mg P L^{-1} (344 to 891) and 1600 mg N L^{-1} (829 to 2320),[24] the annual mass of nutrients in US septage is an estimated 12 500 000 kg of P and 33 300 000 kg of N. These nutrients could offset synthetic fertilizer and its associated economic and environmental impacts. Reimagined septage management integrates each step of the septage process: collection, transport, treatment, and disposal/reuse.

The recovery of beneficial nutrients, energy, and water from septage begins by collecting it from the septic tank. State wastewater codes can promote proper construction and sealing of new tanks, along with regular inspection of older tanks, ensuring that they function properly to prevent contamination of groundwater and store future septage resources. National efforts like the EPA's SepticSmart campaign, amplified by state and county agencies, can assist local regulators and professionals to inform septic system owners of maintenance practices, including pumping frequency. However, leaky septic tanks may never be pumped because their untreated contents seep into the underlying soil and possibly groundwater.[2] Timely pumping of septic tanks by pumpers can reduce failures, protect surface and groundwater resources, and promote increased recovery of resources. Dewatering septage while pumping, feasible but limited in application, can reduce transport costs associated with water weight, saving fuel and allowing pumpers to service more customers. Logistics of septage transport can be optimized *via* software programs or artificial intelligence to reduce the environmental impacts associated with long transport distances.[25,26]

There is untapped potential to recover nutrients in treated septage for beneficial purposes and provide economic opportunities for communities on decentralized wastewater systems. The most promising option to increase resource recovery is to increase the quantity of septage that is transported to wastewater treatment plants, especially those that already practice resource recovery. Established treatment technologies at wastewater treatment plants that promote resource recovery include composting and anaerobic digestion (Table 1);[2] these technologies produce useful products such as biomethane and compost while simultaneously reducing greenhouse gas emissions and nutrient discharge.[27] Other established nutrient management technologies such as struvite precipitation and ammonia stripping can also be integrated with anaerobic digestion to remove or ideally recover nutrients and offset the costs and environmental impacts generated from synthetic fertilizer production and transport. Emerging thermal technologies such as pyrolysis or hydrothermal carbonization can also be used at wastewater treatment plants to treat septage and recover beneficial products such as biochar or hydrochar, which is a durable carbon product and can be applied to land for agricultural purposes or used to treat wastewater.[28–30]

4. Barriers to change and paths forward

The lack of comprehensive data on septic systems at a national level presents a formidable barrier to improving septage management practices and capturing resources. Since the US Census Bureau discontinued collecting national data on septic systems in 1990, there has been no centralized effort to track the number, location, and condition of these systems across the country.[31] This data gap severely hampers efforts to assess the full scope of environmental impacts, identify high-risk areas, and develop targeted interventions. The National Environmental Services Center previously attempted to fill this void by conducting periodic national assessments, but these efforts were limited in scope and frequency and no longer occur.[32] Efforts are underway in the industry to revive data collection regarding septic use; septic use will be added to the American Community Survey by the U.S. Census Bureau.[33]

The state-specific manner of septic system regulation and management further requires coordinated efforts by governments, businesses and academia to reimagine septage management due to varying standards and best practices. The authority in charge of permitting septic systems varies by state: 41% health department, 27% county, 19% state, and 13% other.[32] This fragmented regulatory landscape leads to significant variations in installation standards, maintenance requirements, and enforcement practices across different

Table 1 Potential septage management strategies and their opportunities for resource recovery and important operational variables

Management strategies	Current status	Opportunity for resource recovery	Important operational variables
Surface land application	Established	N and P content	Volume, nutrient content
Landfill	Established	CH_4 capture	Volume, C content
Composting	Established	N and P content	Storage space and distribution
Anaerobic digestion	Established	CH_4 yield	Temperature, time, pH, feedstock quantity
Aerobic digestion	Established	None	Temperature, residence time
Chlorine oxidation	Established	None	Contact time
Stabilization lagoon	Established	Algae	Residence time
Pyrolysis	Emerging	Biochar, bio-oil yield	Temperature, residence time
Struvite precipitation	Emerging	N and P recovery	pH, molar ratio of Ca Mg, or NH_4 to PO_4
Ammonia stripping	Emerging	N recovery	Temperature, pH, NH_4 N load ratio

regions. For instance, some jurisdictions require regular inspections and pumping, while others have no such mandates. This lack of uniformity makes it difficult to implement widespread improvements or innovations in septage management without regional or state coordination.

Public perception and awareness issues may also present significant barriers to changing septage management practices. Many homeowners lack understanding of proper septic system maintenance and the potential environmental impacts of failing systems.[34,35] Research in rural communities has found a disconnect between perceived and actual water quality, with many residents unaware of the potential impact of their septic systems on local water resources.[34,35] This knowledge gap can lead to neglect and delayed repairs, exacerbating environmental risks. The "out of sight, out of mind" nature of septic systems often results in homeowners paying little attention to their systems until a failure occurs, by which time environmental damage may have already occurred. Furthermore, most people remain unaware of what septage is and how it is processed, compounding the broader issue of inadequate education regarding proper septic system maintenance.

Financial constraints also pose a significant challenge to improving septage management practices, particularly in economically disadvantaged areas. Upgrading or replacing septic systems can be prohibitively expensive for many homeowners, with costs potentially running into tens of thousands of dollars.[36] In areas with aging infrastructure or systems vulnerable to climate change impacts, the need for upgrades may be widespread, creating a substantial financial burden for entire communities. Many communities have limited staff to permit systems and ensure compliance with regulations. Technical assistance opportunities, such as the EPA's Closing America's Wastewater Access Gap Initiative, can provide under resourced communities in rural areas with help to apply for funding and perform the technical and engineering analysis needed for community-oriented solutions. However, this Initiative takes a localized approach to assist specific communities across the US and does not address issues of septage management. The high costs associated with system improvements and limited regulatory professionals can result in continued use of outdated or failing systems, perpetuating environmental risks and limiting the capture of septage.

Emerging contaminants, particularly per- and polyfluoroalkyl substances (PFAS), represent another significant barrier to septage management and resource recovery. The ubiquitous presence of PFAS in domestic wastewater and their persistence in the environment have prompted increasing regulatory scrutiny, creating substantial uncertainty for wastewater utilities.[37,38] Maine has implemented stringent regulations restricting land application of biosolids containing PFAS, while others like Georgia are considering regulations requiring land application site monitoring wells to meet drinking water maximum contaminant levels.[39,40] These evolving regulatory frameworks have the potential to severely limit conventional septage management options, particularly land application and the acceptance of septage at wastewater treatment plants that produce biosolids for land application. Advanced thermal treatment technologies, such as high-temperature incineration, pyrolysis, and hydrothermal processes, offer promising methods for PFAS destruction in septage and biosolids.[41,42] However, these technologies often require significant capital investment, specialized expertise, and higher operational costs compared to traditional management methods, potentially limiting their widespread adoption despite their effectiveness in breaking down PFAS compounds.[43] While the evolving PFAS regulatory landscape presents challenges, it also creates opportunities for innovation in septage treatment technologies that can simultaneously address contaminant concerns and enhance resource recovery potential, driving the industry toward more sustainable management approaches.[44,45]

The lack of standardized protocols for assessing damage to septic systems from natural disasters is another significant barrier. When systems are damaged from flooding, fires, or earthquakes but continue operating without proper assessment, they may leak septage into the environment rather than retaining it for beneficial collection and reuse. Cox *et al.* highlighted the need for a centralized system to collect post-storm inspection reports and performance monitoring data.[36] Such a system would help identify compromised tanks that require repair to properly contain septage, while also informing pumping schedules to maximize resource recovery before potential system failures. Visual inspections alone may not be sufficient to determine if a system's septage containment has been compromised. Advanced monitoring approaches like flow metering and virtual tracking could help optimize septage collection timing and identify tanks at risk of failure before they begin leaking valuable resources. Many communities lack the data, tools, and regulatory frameworks to proactively address these vulnerabilities, resulting in lost opportunities for septage capture and resource recovery when systems fail. These barriers collectively impede the effective management and utilization of septage as a valuable resource. Overcoming these challenges through improved monitoring and assessment is crucial for maximizing septage collection and realizing its full potential as a source of nutrients, energy, and water. By addressing these barriers, we can pave the way for more sustainable and efficient septage management practices that benefit both communities and the environment.

Moving forward, these barriers to change will need to be overcome at each step of the septage process to fully realize the social, environmental, and economic benefits associated with reimagined septage management (Fig. 2). All steps of the septage process would benefit from policy best practices, increased stakeholder engagement, data collection, integration of machine learning, and climate change adaptation to overcome these barriers. For example, opportunities exist to use satellite imagery to fill in missing data like locations of septic systems.[46,47] The barrier of lack of comprehensive data could also be addressed by integrating data collection protocols into the regulatory framework, using academic models or developing voluntary collection efforts for permitting authorities. These data collection protocols could also include data from stakeholders including homeowners, septic service providers, local health departments, environmental agencies, and wastewater treatment plant operators.

A lack of centralized economic resources can further complicate the situation.[48] Financial constraints for maintenance and climate change adaptation could be addressed by increased funding (and awareness of such funding) to decentralized communities. The Bipartisan Infrastructure Law provides $11.7 billion for the Clean Water State Revolving Fund (CWSRF), plus an additional $1 billion for the CWSRF to address emerging contaminants.[1] These funds can be used for technical assistance to help communities gain access to resources but cannot be used for long-term maintenance or septage management.[49] Despite this level of funding, a gap in necessary funding is still projected and the level of state investments across the US is also unclear. The barrier of inconsistent septic system design, permitting, operation, and maintenance could be addressed by developing best practices that could be modified at the State or County level.

While this Perspective focuses primarily on the US context, valuable lessons can be drawn from international approaches to septage management. In Europe, Ireland has implemented a National Inspection Plan for domestic wastewater treatment systems that employs a risk-based approach to inspections, with 1110 inspections conducted in 2020, finding a 54% compliance rate.[50,51] Costa Rica has developed a National Wastewater Sanitation Policy with goals to increase proper septage management in rural areas where approximately 76.4% of households use septic systems.[52] Developing countries have opportunities to leapfrog conventional approaches by implementing innovative septage management technologies from the outset. The Gates Foundation's reinvent the toilet initiative exemplifies this potential through next-generation technologies that treat waste onsite without sewers or external water sources.[28,53–55] Such advanced systems complement the emerging strategies outlined in Table 1 and demonstrate how innovations from abroad can inform and potentially accelerate the transformation of septage management approaches in U.S. rural and underserved communities.

Many challenges and opportunities exist for septic tank management and septage utilization in the US. As we seek more sustainable approaches, we must consider how

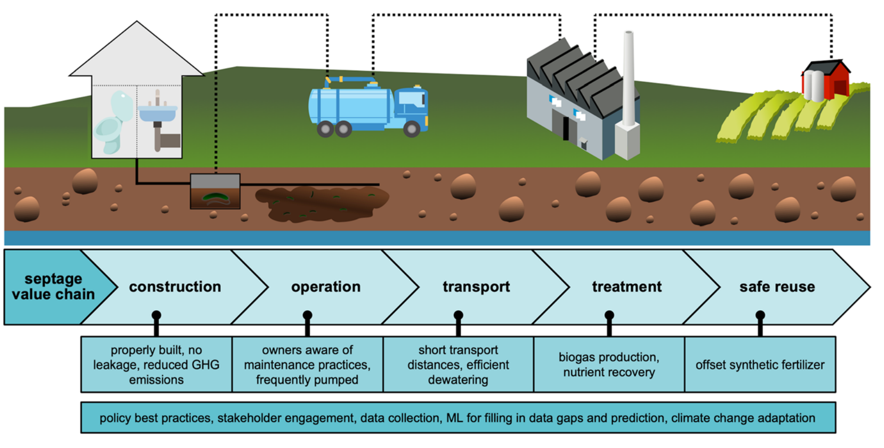

Fig. 2 The septage value chain for septic tanks, illustrating opportunities for improved management, resource recovery, and environmental protection. The chain encompasses construction, operation, transport, treatment, and safe reuse.

changing precipitation patterns and rising temperatures may impact septic system functionality and environmental risks. More frequent pumping of septic tanks could play a dual role in promoting resilience and adaptation. By improving the efficiency of septic tank pumping intervals with data or technologies that validate operation and treatment effectiveness, we can potentially decrease methane emissions, a potent greenhouse gas.[56] Additionally, the recovered septage can be leveraged for resource recovery through technologies like anaerobic digestion with biomethane capture or pyrolysis for biochar production. These processes not only reduce greenhouse gas emissions but also create valuable products like renewable energy and soil amendments.

5. Conclusion

Septage is an untapped waste stream that could be utilized for resource recovery and its potential economic, environmental, and social benefits. Current approaches for septage management including land application, treatment at wastewater treatment plants, and treatment at independent septage treatment plants result in negative environmental impacts such as groundwater contamination and greenhouse gas emissions, both of which will be exacerbated due to climate change. Reimagined septage management could promote recovery of beneficial nutrients, energy, and water. Barriers such as lack of comprehensive data, decentralized regulation and management, negative public perception, and climate change can be overcome *via* policy best practices, increased stakeholder engagement, increased data collection, integration of machine learning, and climate change adaptation. Improved management of the annual 5.5 billion gallons of US septage could provide substantial economic, environmental, and social benefits due to reduced environmental contamination and increased recovery of resources.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

Author contributions

Kevin D. Orner: conceptualization, investigation, methodology, project administration, supervision, visualization, writing – original draft, writing – review & editing; Lewis S. Rowles: conceptualization, investigation, methodology, visualization, writing – original draft, writing – review & editing; Sara Heger: methodology, writing – review & editing; Ben Howard: writing – review & editing.

Conflicts of interest

The authors declare no conflicts of interest.

References

1 J. Maxcy-Brown, M. A. Elliott and B. Bearden, Household level wastewater management and disposal data collection in the U.S.: the history, shortcomings, and future policy implications, *Water Policy*, 2023, **25**, 927–947.
2 U.S. EPA, Decentralized Systems Technology Fact Sheet: Septage Treatment/Disposal, U.S. EPA, Washington, D.C., 1999.
3 U.S. Census Bureau, Historical Census of Housing Tables: Sewage Disposal, 1990.
4 US EPA, *Handbook Septage Treatment and Disposal*, 1994, https://nepis.epa.gov/Exe/ZyNET.exe/30004ARR.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1981+Thru+1985&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C81thru85%5CTxt%5C00000002%5C30004ARR.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL#, (accessed 30 September 2024).
5 US EPA, Guide to Septage Treatment and Disposal, https://www.epa.gov/biosolids/guide-septage-treatment-and-disposal, (accessed 6 October 2024).
6 E. Z. Harrison and M. Moffe, Septage quality and its effect on field life for land applications, *J. Am. Water Resour. Assoc.*, 2003, **39**, 87–97.
7 A. Bakchan and K. D. White, Sustainable Development in Rural Underserved Communities through Improved Responsible Management of Decentralized Wastewater Infrastructure: A Focus on the Alabama Black Belt, *Environ. Sci. Technol.*, 2024, acs.est.4c01170.
8 R. Shet and S. Mutnuri, Anaerobic Co-digestion of Organic Fraction of Municipal Solid waste and Septage for Sustainable Waste Treatment: A Case Study from Goa, India, *European Journal of Energy Research*, 2021, **1**, 1–8.
9 CalRecycle, Analysis of the Progress Toward the SB 1383 Organic Waste Reduction Goals, California Department of Resources Recycling and Recovery, 2020.
10 R. T. Bachmann, A. J. Saul and R. G. J. Edyvean, Investigating and modelling the development of septic sewage in filled sewers under static conditions: A lab-scale feasibility study, *Sci. Total Environ.*, 2007, **388**, 194–205.
11 C. D. Beal, E. A. Gardner and N. W. Menzies, Process, performance, and pollution potential: A review of septic tank - soil absorption systems, *Soil Res.*, 2005, **43**, 781.
12 H. M. Murphy, S. McGinnis, R. Blunt, J. Stokdyk, J. Wu, A. Cagle, D. M. Denno, S. Spencer, A. Firnstahl and M. A. Borchardt, Septic Systems and Rainfall Influence Human Fecal Marker and Indicator Organism Occurrence in Private Wells in Southeastern Pennsylvania, *Environ. Sci. Technol.*, 2020, **54**, 3159–3168.

13 E. Dreelin, R. Ives, S. Molloy and J. Rose, Cryptosporidium and Giardia in Surface Water: A Case Study from Michigan, USA to Inform Management of Rural Water Systems, *Int. J. Environ. Res. Public Health*, 2014, **11**, 10480–10503.

14 M. C. Allaire, B. Brusco, A. Bakchan, M. A. Elliott, M. A. Jordan, J. Maxcy-Brown and K. D. White, Water and wastewater infrastructure inequity in unincorporated communities, *npj Clean Water*, 2024, **7**, 125.

15 C. Meile, W. P. Porubsky, R. L. Walker and K. Payne, Natural attenuation of nitrogen loading from septic effluents: Spatial and environmental controls, *Water Res.*, 2010, **44**, 1399–1408.

16 A. H. Cox, G. W. Loomis and J. A. Amador, Preliminary Evidence That Rising Groundwater Tables Threaten Coastal Septic Systems, *J. Sustain. Water Built Environ.*, 2019, **5**, 04019007.

17 J. A. Cooper, G. W. Loomis and J. A. Amador, Hell and High Water: Diminished Septic System Performance in Coastal Regions Due to Climate Change, *PLoS One*, 2016, **11**, e0162104.

18 O. US EPA, Climate Adaptation Plans, **https://www.epa.gov/climate-adaptation/climate-adaptation-plans**, (accessed 6 October 2024).

19 US EPA, Safeguarding Against Climate Change Impacts: A Resource Guide for Onsite Wastewater Treatment Systems, 2024.

20 J. A. Izbicki, Fate of Nutrients in Shallow Groundwater Receiving Treated Septage, Malibu, CA, *Groundwater*, 2014, **52**, 218–233.

21 M. Ghanbari, M. Arabi, S.-C. Kao, J. Obeysekera and W. Sweet, Climate Change and Changes in Compound Coastal-Riverine Flooding Hazard Along the U.S. Coasts, *Earths Future*, 2021, **9**, e2021EF002055.

22 H. L. Leverenz, G. Tchobanoglous and J. Darby, *Evaluation of greenhouse gas emissions from septic systems*, Water Environment Research Foundation, IWA Publishing, Alexandria, VA, London, UK, 2010.

23 US EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008*, 2010.

24 R. C. Summerfelt and C. R. Penne, Septic Tank Treatment of the Effluent from a Small-Scale Commercial Recycle Aquaculture System, *N. Am. J. Aquac.*, 2007, **69**, 59–68.

25 M. A. Hannan, M. S. Hossain Lipu, M. Akhtar, R. A. Begum, M. A. Al Mamun, A. Hussain, M. S. Mia and H. Basri, Solid waste collection optimization objectives, constraints, modeling approaches, and their challenges toward achieving sustainable development goals, *J. Cleaner Prod.*, 2020, **277**, 123557.

26 S. Das and B. Kr, Bhattacharyya, Optimization of municipal solid waste collection and transportation routes, *Waste Manage.*, 2015, **43**, 9–18.

27 K. D. Orner, S. Smith, S. Nordahl, A. Chakrabarti, H. Breunig, C. D. Scown, H. Leverenz, K. L. Nelson and A. Horvath, Environmental and Economic Impacts of Managing Nutrients in Digestate Derived from Sewage Sludge and High-Strength Organic Waste, *Environ. Sci. Technol.*, 2022, **56**, 17256–17265.

28 L. S. Rowles, V. L. Morgan, Y. Li, X. Zhang, S. Watabe, T. Stephen, H. A. C. Lohman, D. DeSouza, J. Hallowell, R. D. Cusick and J. S. Guest, Financial Viability and Environmental Sustainability of Fecal Sludge Treatment with Pyrolysis Omni Processors, *ACS Environ. Au*, 2022, **2**, 455–466.

29 N. Saha, K. McGaughy, S. C. Davis and M. T. Reza, Assessing hydrothermal carbonization as sustainable home sewage management for rural counties: A case study from Appalachian Ohio, *Sci. Total Environ.*, 2021, **781**, 146648.

30 M. T. Zaki, L. S. Rowles, D. A. Adjeroh and K. D. Orner, A Critical Review of Data Science Applications in Resource Recovery and Carbon Capture from Organic Waste, *ACS ES&T Eng.*, 2023, **3**, 1424–1467.

31 K. LaFond, Infographic: America's Septic Systems, **https://www.circleofblue.org/2015/world/infographic-americas-septic-systems/**, (accessed 15 November 2023).

32 National Environmental Services Center, *Assessment of U.S. Onsite System Installations, 2015 through 2018*, National Environmental Services Center, Morgantown, WV, 2018.

33 M. Cromwell, P. Massarone and M. Virgile, *2022 American Community Survey Content Test Evaluation Report: Sewer*, US Census Bureau.

34 L. S. Rowles III, A. I. Hossain, I. Ramirez, N. J. Durst, P. M. Ward, M. J. Kirisits, I. Araiza, D. F. Lawler and N. B. Saleh, Seasonal contamination of well-water in flood-prone colonias and other unincorporated U.S. communities, *Sci. Total Environ.*, 2020, **740**, 140111.

35 L. S. Rowles, T. Whittaker, P. M. Ward, I. Araiza, M. J. Kirisits, D. F. Lawler and N. B. Saleh, A Structural Equation Model to Decipher Relationships among Water, Sanitation, and Health in Colonias-Type Unincorporated Communities, *Environ. Sci. Technol.*, 2020, **54**, 16017–16027.

36 A. H. Cox, M. J. Dowling, G. W. Loomis, S. E. Engelhart and J. A. Amador, Geospatial Modeling Suggests Threats from Stormy Seas to Rhode Island's Coastal Septic Systems, *J. Sustain. Water Built Environ.*, 2020, **6**, 04020012.

37 Treatment Mitigation Strategies for Poly- and Perfluorinated Chemicals, **https://www.waterrf.org/research/projects/treatment-mitigation-strategies-poly-and-perfluorinated-chemicals**, (accessed 4 March 2025).

38 I. Ross, J. McDonough, J. Miles, P. Storch, P. Thelakkat Kochunarayanan, E. Kalve, J. Hurst, S. S. Dasgupta and J. Burdick, A review of emerging technologies for remediation of PFASs, *Remediation Journal*, 2018, **28**, 101–126.

39 Georgia Department of Natural Resources, *Per- and Polyfluorinated Substances (PFAS) Permitting Strategy*, **https://epd.georgia.gov/document/document/draft-pfas-strategy-22025/download**, (accessed 4 March 2025).

40 C. R. Gravesen, L. S. Lee, Y. J. Choi, M. L. Silveira and J. D. Judy, PFAS release from wastewater residuals as a function of composition and production practices, *Environ. Pollut.*, 2023, **322**, 121167.

41 E. Crownover, D. Oberle, M. Kluger and G. Heron, Perfluoroalkyl and polyfluoroalkyl substances thermal desorption evaluation, *Remediation Journal*, 2019, **29**, 77–81.

42 A. L. Duchesne, J. K. Brown, D. J. Patch, D. Major, K. P. Weber and J. I. Gerhard, Remediation of PFAS-Contaminated Soil and Granular Activated Carbon by Smoldering Combustion, *Environ. Sci. Technol.*, 2020, **54**, 12631–12640.

43 L. J. Winchell, J. J. Ross, M. J. M. Wells, X. Fonoll, J. W. Norton and K. Y. Bell, Per- and polyfluoroalkyl substances thermal destruction at water resource recovery facilities: A state of the science review, *Water Environ. Res.*, 2021, **93**, 826–843.

44 N. Bolan, B. Sarkar, Y. Yan, Q. Li, H. Wijesekara, K. Kannan, D. C. W. Tsang, M. Schauerte, J. Bosch, H. Noll, Y. S. Ok, K. Scheckel, J. Kumpiene, K. Gobindlal, M. Kah, J. Sperry, M. B. Kirkham, H. Wang, Y. F. Tsang, D. Hou and J. Rinklebe, Remediation of poly- and perfluoroalkyl substances (PFAS) contaminated soils – To mobilize or to immobilize or to degrade?, *J. Hazard. Mater.*, 2021, **401**, 123892.

45 M. C. S. Costello and L. S. Lee, Sources, Fate, and Plant Uptake in Agricultural Systems of Per- and Polyfluoroalkyl Substances, *Curr. Pollut. Rep.*, 2020, **10**, 799–819.

46 K. N. Connelly, S. J. Wenger, N. Gaur, J. M. Bateman McDonald, M. Occhipinti and K. A. Capps, Assessing relationships between onsite wastewater treatment system maintenance patterns and system-level variables, *Sci. Total Environ.*, 2023, **870**, 161851.

47 W. Reckling, J. Levine, S. A. C. Nelson and H. Mitasova, Predicting residential septic system malfunctions for targeted drone inspections, *Remote Sens. Appl.: Soc. Environ.*, 2023, **30**, 100936.

48 K. A. Capps, N. Gaur, T. Callahan, A. Orrego, D. Bloyer, K. Higgs and D. Johnson, Disparities between the Demand for On-Site Wastewater Treatment Systems and Treatment Options for Septage, *ACS ES&T Eng.*, 2021, **1**, 2251–2258.

49 US EPA, Funding for Septic Systems, https://www.epa.gov/septic/funding-septic-systems, (accessed 30 September 2024).

50 P. Hynds, O. Naughton, E. O'Neill and S. Mooney, Efficacy of a national hydrological risk communication strategy: Domestic wastewater treatment systems in the Republic of Ireland, *J. Hydrol.*, 2018, **558**, 205–213.

51 E. P. Agency, Domestic Waste Water Treatment System Inspections 2020, https://www.epa.ie/publications/compliance–enforcement/waste-water/domestic-waste-water-treatment-system-inspections-2020.php, (accessed 4 March 2025).

52 MINAE, Política Nacional de Saneamiento en Aguas Residuales 2016–2045, 2016.

53 H. Lohman, Y. Li, X. Zhang, V. Morgan, S. Watabe, L. S. Rowles, R. Cusick and J. Guest, Defining economic and environmental typologies across 77 countries to prioritize opportunities for non-sewered sanitation, *ChemRxiv*, 2025, preprint, DOI: 10.26434/chemrxiv-2025-zb1r0.

54 S. Watabe, H. A. C. Lohman, Y. Li, V. L. Morgan, L. S. Rowles, T. Stephen, H.-Y. Shyu, R. A. Bair, C. J. Castro, R. D. Cusick, D. H. Yeh and J. S. Guest, Advancing the Economic and Environmental Sustainability of the NEWgenerator Nonsewered Sanitation System, *ACS Environ. Au*, 2023, **3**(4), 209–222.

55 Reinvent the Toilet Challenge, https://www.gatesfoundation.org/our-work/programs/global-growth-and-opportunity/water-sanitation-and-hygiene/reinvent-the-toilet-challenge-and-expo, (accessed 4 March 2025).

56 J. Moonkawin, L. T. Huynh, M. Y. Schneider, S. Fujii, S. Echigo, L. P. H. Nguyen, T.-H. T. Hoang, H. T. Huynh and H. Harada, Challenges to Accurate Estimation of Methane Emission from Septic Tanks with Long Emptying Intervals, *Environ. Sci. Technol.*, 2023, **57**, 16575–16584.

