COLD WEATHER ANAEROBIC DIGESTERS: CHALLENGES AND OPPORTUNITIES

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Executive Summary

In Alaska, over 3,000 households currently use unpiped sanitation systems to collect human waste and nearly 80% of rural households rely on diesel to meet their energy needs. A consistent concern and priority that is expressed to the U.S. Environmental Protection Agency (EPA) from Alaska Native Villages is the need for basic sanitation and treatment options for raw sewage. The EPA is interested in exploring the multi-benefit use and feasibility of anaerobic digestion (AD) for both sanitation and energy improvements for off-grid Alaskan communities. AD is a proven and effective biological treatment process that relies on microorganisms to break down organic matter (OM), effectively reducing pathogens and producing biogas as a byproduct and potential energy source.

This research report summarizes findings from a landscape analysis of AD with a focus on identifying 1) where AD has been used in cold weather or high elevation locations; 2) challenges associated with implementing AD systems; and 3) opportunities for funding and implementing cold weather AD design in Alaskan communities. The landscape analysis involved conducting a literature review, interviewing experts in the field, and reviewing current technologies to identify challenges, gaps, and opportunities for implementing anaerobic digesters in rural Alaskan communities. After data cleaning, 32 out of the 50 experiments reported successfully testing out AD in 20°C or colder operating temperatures. The most significant barriers to implementing AD systems include freezing temperatures, having trained operators and consistent monitoring, affordability and access.

Overall, the initial analysis indicates that AD systems can operate at low temperatures, effectively achieve pathogen reduction, and generate biogas (although limited). Yet, there are persistent gaps in the implementation of field-scale cold weather AD systems, especially in the Arctic and sub-Arctic regions. Key recommendations include:

- Conducting field-scale testing of digesters to account for various design and operational strategies.
- Implementing centralized systems for easier operation and maintenance.
- Incorporating external heating, with an emphasis on both passive and active methods.
- Investigating improved and reliable collection and conveyance strategies.
- Involving and integrating community priorities, values, and feedback throughout the design and implementation processes

If implemented and operated properly, AD has the potential to improve both human and environmental health with numerous social and economic benefits.

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Sanitation needs and solutions for rural Alaskan communities

Currently, over 3,000 Alaskan households use unpiped sanitation systems, like "honey buckets," to collect human waste. The honey buckets are often lined with plastic bags and require residents to haul their waste to collection hoppers or directly to sewage lagoons (Figure 1). This current honey bucket and hauling system poses numerous sanitation, public health, social, and environmental concerns including spillage, exposure to raw sewage, and a burden to those physically incapable of moving their waste. Temperatures vary across Alaska with average lows in the -30s and highs around 15°C.[1] Diesel is used as the primary fuel for heating homes; nearly 80% of Alaskan rural households rely on diesel to meet their energy needs with the poorest households spending half of their annual income on heating fuel and electricity.[2] This reliance on diesel results in indoor air pollution, high rates of child asthma, and high fuel costs. When it comes to the Sustainable Development Goals, rural and off-grid communities are often left behind in both water, sanitation, and hygiene services and energy.[3]

A. B. C.

Figure 1. Current sanitation system for the tribal village of Atmautluak, located in western Alaska. Fig 1a - honey buckets used to collect human urine and feces in a home. Fig 1b – a young native hauling honey bucket waste to the hopper. Fig 1c – a hopper disposing of human waste into a sewage lagoon. All photos borrowed from https://dec.alaska.gov/water/water-sewer-challenge/photo-gallery/.

[1] Markon, C. J., Trainor, S. F., & Chapin III, F. S. (2012). The United States National Climate Assessment—Alaska Technical Regional Report. In The United States National Climate Assessment—Alaska Technical Regional Report (USGS Numbered Series No. 1379; Circular, Vol. 1379, p. 166). U.S. Geological Survey. https://doi.org/10.3133/cir1379

[2] Kohler, M., & Schutt, E. (2012). Energy for a Sustainable Alaska—The Rural Conundrum (p. 42). Commonwealth North. https://www.commonwealthnorth.org/download/Reports/2012_CWN%20Report%20-%20Energy%20for%20a%20Sustainable%20Alaska%20-%20The%20Rural%20Conundrum.pdf

[3] Mattos, K. J. (2017). Water Resources and Reuse for Remote Arctic Communities [M.S., University of Colorado at Boulder]. https://www.proquest.com/docview/2019646776/abstract/75123C288A3F44B4PQ/1

Part of the U.S. Environmental Protection Agency's (EPA) Region 10's Tribal trust responsibilities include assisting Alaska Native Villages with sanitation. A consistent concern and priority that is expressed to the EPA from Alaska Native Villages via EPA-Tribal Environmental Plans (ETEPs) is the need for basic sanitation and treatment options for raw sewage. For these reasons, the EPA is interested in exploring the multi-benefit use of anaerobic digestion (AD) for both sanitation and energy improvements.

AD is a proven and effective biological treatment process that relies on microorganisms to break down organic matter (OM). AD reduces pathogens, stabilizes waste, and produces biogas which can be used as a source of renewable energy. AD has been used for centuries as a sanitation solution for treating human and animal waste and has more recently capitalized on using the biogas byproduct as an energy source. Yet most applications of AD systems exist in warmer, lower latitude areas resulting in a lack of data on the feasibility and application of AD in cold and extreme climates. Operating temperature is a vital performance parameter for the successful operation of AD systems and typically microbes perform best in the mesophilic (30-40°C) and thermophilic (45-60°C) temperature ranges. However, cold temperature performance could be improved by modifying other design factors, like increasing how long the waste is in the digester (solids retention time (SRT)) and incorporating passive and active heating features.

The EPA aims to test out the feasibility of AD systems in Arctic and sub-Arctic temperatures to determine the suitability of using AD as both a sanitation (waste stabilization) and clean energy solution for off-grid Alaskan communities. This report summarizes findings from an initial landscape analysis of AD with a focus on identifying 1) where AD has been used in cold weather or high elevation locations; 2) challenges associated with implementing AD systems; and 3) opportunities for funding and implementing cold weather AD design in Alaskan communities.

Landscape Analysis

The landscape analysis involved conducting a literature review, interviewing experts in the field, and reviewing current technologies to identify challenges, gaps, and opportunities for implementing anaerobic digesters in rural Alaskan communities.

For the literature review, a title search was conducted using the Web of Science and Google Scholar platforms in order to find relevant academic literature around cold temperature AD. The following search terms were used in various combinations: anaerobic digestion or digester, cold weather or climate or temperature(s), high elevation, off-grid or rural or remote communities, and biogas energy. Numerous parameters were extracted from the literature studies and organized in a database with a focus on gathering information regarding operating temperatures, organic loading size, feedstock type, biogas production potential, and reactor type. Afterward, R Studio was used to produce data visualizations.

Semi-structured interviews were conducted where experts were asked a range of questions depending on their area of expertise but included a focus on either AD or implementing sanitation services in off-grid communities. After the interviews, information was synthesized and organized into broad categories addressing design considerations, success factors, failure factors, barriers, and funding information. The following experts were interviewed: Dr. Kaitin Mattos (University of Colorado Boulder); Dr. Michael Marsolek (Seattle University and Mt. Everest Biogas Project), Dr. Jaime Martí-Herrero (Universidad Regional Amazónica Ikiam), Max Krause (EPA Office of Research and Development), Dr. Sherri Cook (University of Colorado Boulder), and Cheryl Rosa (Deputy Director, U.S. Arctic Research Commission).

Results: Landscape analysis

From the initial literature review search, findings from 62 papers representing 129 experiments (some papers tested multiple anaerobic digestion systems or conditions) were incorporated into the main database. There was a mix of AD systems used throughout the studies including batch reactors, low-cost tubular plug flow reactors, continuously stirred tank reactors, fixed dome, expanded granular sludge bed, anaerobic filters, upflow anaerobic sludge blanket, hydrolytic up-flow sludge bed, and fluidised bed. Of the total experiments reported, 58 were lab-scale, 15 pilot studies, 14 field-deployed, 2 lab and pilot, 1 lab and field-deployed, and 4 pilot and field-deployed -- thus signifying a need for additional field-scale testing.

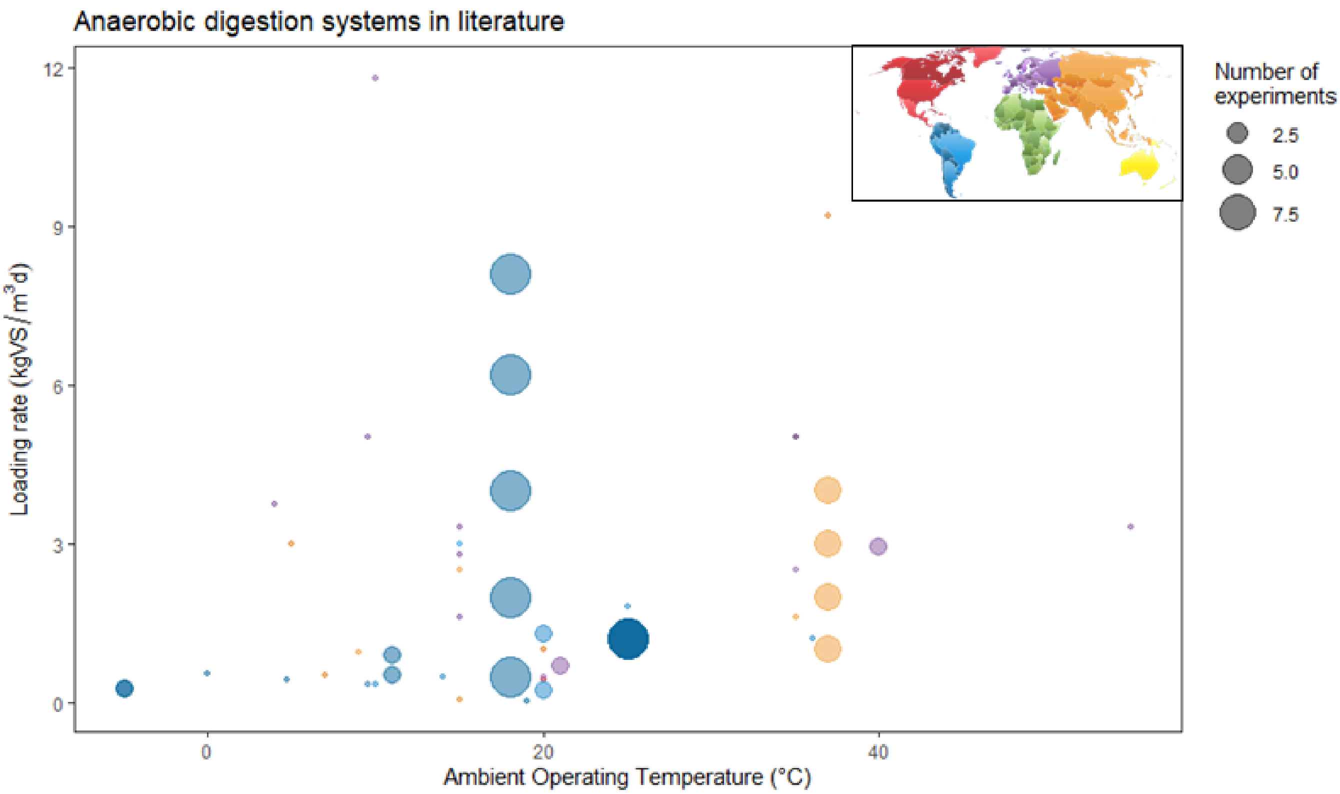

Figure 2 Results from the literature review showing a spatial comparison of operating temperatures and organic loading rates for anaerobic digestion systems implemented globally.

Figure 2 shows a plot comparison of ambient operating temperatures and organic loading rates of anaerobic digesters from 50 experiments (35 papers). The remaining studies were not included due to either missing information or inconsistencies with unit reporting. The bubble size indicates the number of experiments included in a specific study. The color is indicative of location, where blues are South American countries (n=22), reds are North American countries (n=1), purples are European countries (n=15), and oranges are Asian countries (n=12). There were no studies reported from Africa (green), Australia (yellow), or Antarctica (not shown). Specific countries included were Bolivia, Brazil, Canada, China, Columbia, Czech Republic, Denmark, France, Germany, India, Ireland, Italy, Japan, Nepal, Peru, Spain, and the United Kingdom. Of the 50 included experiments, 32 reported successfully testing out AD in 20°C or colder operating temperatures. Most of the studies tested lower organic loading rates which could be either promising or present an additional barrier for smaller-scale implementations in non-piped communities.

Overall, so far, the results from the literature demonstrate that while cold temperature AD systems have been tested, there is a need for more field testing specifically examining implementation in Alaska.

Results: challenges

Temperature

Low and fluctuating temperatures are a key barrier when it comes to maintaining a productive environment for microbes. Freezing issues can inhibit microbial processes, significantly reduce biogas production, and could lead to clogging and backups in the system. Fluctuating temperatures prevent consistency in the microbial population and could cause destabilization and system failure.

Operations

AD systems require trained staff for both startup and operation and maintenance (O&M). Two significant challenges during startup include slow hydrolysis of OM and slow growth of methanogens.[4] The likelihood of destabilization is greater with smaller communities and villages where digester influent may be variable in both quantity and quality. Trained operators and consistent monitoring are essential, which may require bringing in a trained operator or investing in and implementing training programs for community members. Either way, retention of trained personnel should be considered.

Monitoring for the health of the digester includes a) maintaining an ideal pH (6.8 - 7.4) inside the digester and b) optimal C/N ratios -- for enough nitrogen to maintain cell biomass and biogas production and also enough carbon to prevent ammonia inhibition or toxicity.[5] For many of these reasons, there is an inherent complexity that accompanies the successful operation of an AD system, yet increased complexity can potentially increase vulnerability for breakage or failure. EPA guidelines can help establish clear and functional requirements yet should avoid being overly prescriptive in requiring excessively complex systems.

Cost

The cost of installation, heating, and ongoing maintenance should also be considered when implementing AD systems in off-grid communities. Accessing certain communities can present an initial barrier along with the ongoing difficulty of acquiring and affording replacement components. There should be robust compensation programs to account for long-term O&M costs rather than a reliance on grant-funded projects where funds expire. Additionally, the cost of sanitation services should be affordable to households (rather than based on utilities recovering costs) and should be inclusive of all aspects of the sanitation process including billing, collection, hauling, etc.[6] If services are not affordable, community members could reject using the services which could increase costs for others or potentially lead to a system failure.

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[4] Álvarez, J. A., Armstrong, E., Gómez, M., & Soto, M. (2008). Anaerobic treatment of low-strength municipal wastewater by a two-stage pilot plant under psychrophilic conditions. Bioresource Technology, 99(15), 7051–7062. https://doi.org/10.1016/j.biortech.2008.01.013

[5] Mao, C., Feng, Y., Wang, X., & Ren, G. (2015). Review on research achievements of biogas from anaerobic digestion. Renewable and Sustainable Energy Reviews, 45, 540–555. https://doi.org/10.1016/j.rser.2015.02.032

[6] Johnson, B. (2020). A Framework to Assess the Affordability of Residential Water and Sewer Rates in Rural Alaska (p. 56). Village Safe Water Program Department of Environmental Conservation State of Alaska. https://dec.alaska.gov/media/21759/alaska-w-and-s-affordability-model-report.pdf

Collection and Conveyance

Conveyance is of particular concern in communities using honey buckets. The potential for honey bucket bags to tear and leak during transport and hauling results in contamination throughout homes and villages.[7] The lack of affordability, frequency, or reliability of collection systems could result in a buildup of human waste around homes. Additionally, due to physical limitations, hauling might not be an option for elderly or disabled people. Lack of access via roads, ships, or planes or to transportation vehicles like ATVs and snowmobiles creates an additional barrier. Overall, a safer and more reliable collection system that reduces exposure to human waste while considering the downstream impacts on digesters should be implemented in conjunction with an AD system.

Results: design considerations

Given the potential complexity and monitoring required, a centralized community-based AD system would likely be more successful than AD systems at the household level, especially when considering biogas production potential. A centralized system would be easier to maintain and control for water and temperature needs. Additionally, biogas captured from the centralized system could be used to heat the AD systems itself or a community building. Alternatively, decentralized systems could be deployed at the household level which would alleviate some conveyance and hauling issues but would likely present additional operational barriers and the amount of biogas produced might not be sufficient for productive use.

Above-ground systems should be considered in order to avoid permafrost thaw; however, air temperatures tend to be lower and more variable. To address potential temperature barriers, implementing a variety of heating strategies should be considered but all should include insulation and dark-colored materials for better heat absorption. Additionally, thought should be given to selecting construction materials that can withstand extreme conditions (i.e. avoiding plastic that will crack). Insulation should be at least five cm thick, especially with any surface that would have contact with the ground. If the system is on a raised platform, consider heating from below. A greenhouse could potentially be implemented to enclose the AD system but it should be tight-fitting to reduce thermal losses and transparent on top and south-facing to accommodate the low angle of the sun.

It is highly likely that external heating will be required, especially if the digester is expected to operate year-round. The biogas generated from the AD system should contribute to heating, but field-testing will help determine if this would be sufficient and reliable. Exploring existing active heating sources from within homes or nearby buildings and the potential for renewables (like solar and wind energy) would be advisable. Consideration would need to be given to the footprint required for a solar or wind heating system. Heat could potentially also be generated by burning waste.

A seasonal operation strategy could be feasible but would require field testing. A seasonal approach would process waste during the spring and summer months by taking advantage of the increased solar radiation and warmer daily temperatures while during the winter months the AD system would function mostly as safe storage. The seasonal approach would require a larger volume and need to account for start-up times, though diverting gray water and implementing diverting or low flow toilets would assist with reducing the volume requirements. While heating is a significant challenge in Arctic and sub-Arctic regions, a benefit of colder temperatures is that odor is less problematic.

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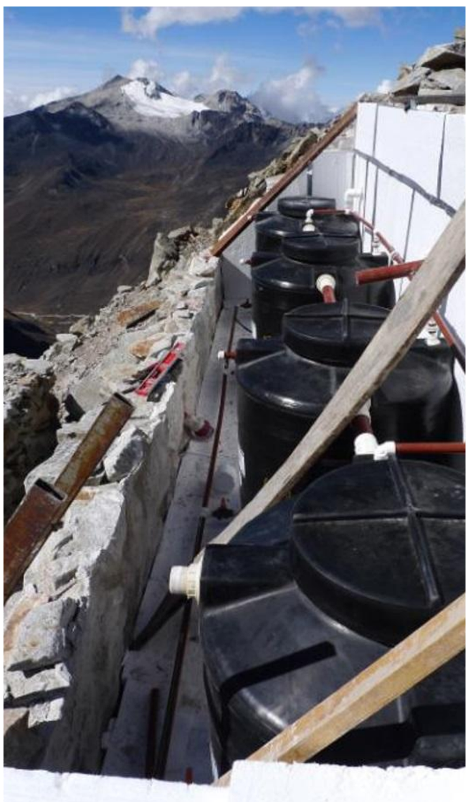
[7] Chambers, M. K., Ford, M. R., White, D. M., Barnes, D. L., & Schiewer, S. (2008). Distribution and Transport of Fecal Bacteria at Spring Thaw in a Rural Alaskan Community. Journal of Cold Regions Engineering, 22(1), 16–37. https://doi.org/10.1061/(ASCE)0887-381X(2008)22:1(16)

Investigating alternative toilet designs, like urine-diverting dry toilets (UDDT) or low-flush toilets, and collection systems like vacuum pumping should be explored. Dry digestion should be considered as it would require less water, reduce digester and effluent volume, and require fewer moving parts (no mixing required).[8] With dry digestion, injecting the AD system with warm water could assist in maintaining warmer temperatures.

In the likelihood that the AD system will require inoculation, an effective seed from a nearby location already functioning at a similar temperature and environment should be used. This could potentially include microbes from a nearby freshwater source or the nearest wastewater treatment plant. The frequency of seeding and co-digestion with food waste should also be explored.

There are several potential designs to consider. Durable and rigid water tanks have been implemented in high elevation locations (Figure 3A) and could be a viable option for withstanding harsh Alaskan conditions and snowpack. Placing them in series would also increase the solids retention time (SRT). Using some type of biofilm carrier, like low-cost plastic soda bottle rings, will increase the internal effective surface area and SRT.[9] Additionally, tubular plug flow reactors (Figure 3B) are low-cost and effective. Tubular digesters are an improved alternative to covered sewage lagoons by saving space and producing and capturing biogas more effectively.

A.



B.

Figure 3 A. Implementation of rigid tank design in a high elevation location (Las Rocas Refuge 5130 masl). B. Tubular digester design including an insulated trench and greenhouse. Images borrowed from Dr. Jaime Martí-Herrero.

[8] Rocamora, I., Wagland, S. T., Villa, R., Simpson, E. W., Fernández, O., & Bajón-Fernández, Y. (2020). Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. Bioresource Technology, 299, 122681. https://doi.org/10.1016/j.biortech.2019.122681

[9] Martí-Herrero, J., Alvarez, R., & Flores, T. (2018). Evaluation of the low technology tubular digesters in the production of biogas from slaughterhouse wastewater treatment. Journal of Cleaner Production, 199, 633–642. https://doi.org/10.1016/j.jclepro.2018.07.148

The required digester volume and the overall footprint of the entire system (including any heating amendments) should be considered. For instance, a seasonal approach would require a larger digester and storage volume while also accounting for potentially long start-up times, whereas designs that support smaller volumes would require less heating but produce less biogas.

Lastly, safety measures should be considered to limit exposure and protect community members and technicians. A well thought out feed inlet for easy bag dropoff might include a textured ramp or bottom to assist in puncturing bags. Installation of gas detectors should also be incorporated, especially if the AD system is going to be indoors.

Recommendations moving forward

Overall, the initial landscape analysis demonstrates that AD systems can operate at low temperatures, effectively achieve pathogen reduction, and generate biogas (although there are limitations). There are persistent gaps in the implementation of field-scale cold weather AD systems, especially in the Arctic and sub-Arctic regions, thus highlighting an opportunity for future research.

Biogas production is more variable depending on the feed, fluctuating temperatures and conditions, and reactor design. Therefore, if the main goal is producing clean energy for community use, then AD might not be the ideal solution, and other methods of cleaner renewable energy should be incorporated or considered.

Moving forward, controlled laboratory testing should continue to test the feasibility of AD operating at cold and fluctuating temperatures, including designing a simple, durable digester in an effort to minimize O&M requirements. Thermodynamic analyses should be conducted to assess both passive and active heating components. AD is first and foremost a sanitation solution, so testing to measure waste stabilization and effluent quality should continue. After extensive laboratory testing, numerous field-scale AD systems should be evaluated within Alaska, including testing different designs, materials, and heating and energy sources that emphasize local options wherever possible.

Throughout the design process, community priorities, values, and feedback should be incorporated and the deployment and implementation of the systems should be tailored to each community. Ultimately, cold climate AD systems might be technically feasible but if a community is reluctant to adopt or use the system this will result in operational failure. Therefore, the willingness of communities to want and use AD systems should be acknowledged and there should be flexibility to avoid overly prescriptive solutions. Implementing solutions that require the least amount of behavior change are generally more successful, therefore, a system should be easy to adopt with immediate utility. In certain communities, the "do it yourself" solutions tend to be more successful but interest should be assessed on a community basis.

Sanitation solutions go beyond improving human and environmental health - they instill dignity. Providing adequate solutions is key but should not be forced. Community engagement matters in ensuring priorities are honored. In parallel to the AD system design, additional thought should be given to improving in-home sanitation by reducing honey buckets and hauling at the household level. If implemented and operated properly, AD has the potential to improve both human and environmental health with numerous social and economic benefits.

Acknowledgments

Thank you to all the interviewees for your time and willingness to share your experiences which contributed to this report.

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