Trident: A Modular Sludge-to-Energy Architecture for Adaptive Anaerobic Digestion

Abstract

Anaerobic digestion (AD) is a widely used strategy for sewage sludge management and renewable energy recovery. However, conventional systems rely on static pretreatment, which constrains efficiency under variable feedstocks. This study introduces *Trident*, a modular and component-validated sludge-to-energy architecture that incorporates active chemical steering, circular material reuse, and data-driven optimization. To maintain compatibility with existing anaerobic digesters, the system architecture was informed by academic frameworks, further methodological guidance was received from The Ohio State University, and experimental validation was conducted through Quasar Energy Group's Laboratory Services and Battelle Memorial Institute.

Three interoperable modules were developed and evaluated. First, a low-voltage electrochemical pretreatment (1.5–3.0 V; ≤0.38 kWh · kg^{-1} VS) was applied upstream of digestion to enhance solubilization and suppress sulfur precursor formation, yielding a 19–33% increase in soluble chemical oxygen demand and a 34–46% reduction in sulfide precursors relative to controls. Second, solids recovered from digested sludge were thermally activated (600–750 °C) and reused as circular gas-conditioning media. Fixed-bed testing with toluene as a model tar compound achieved 61–69% conversion over five regeneration cycles without externally sourced sorbents. Third, Bayesian optimization was implemented within a digital-twin framework. The model integrated biogas flow, methane fraction, pH, and oxidation-reduction potential to coordinate operating setpoints.

Pilot-scale (≈25-gallon) digester simulations, biomethane potential assays, and 30-day stress tests demonstrated an 11–17% increase in methane yield ($0.24 \rightarrow 0.27$ Nm^3 CH$_4 \cdot$ kg^{-1} VS) and a 37% ± 6% reduction in output variability relative to fixed-operation baselines. Although Trident was not evaluated as a fully integrated system, these results indicate that further investment can shift AD from static treatment to adaptive operation.

Keywords: Anaerobic digestion; sewage sludge; electrochemical pretreatment; circular resource reuse; Bayesian optimization; digital twin; biogas upgrading; process systems engineering

Context: I began this research independently while preparing for the Invention Convention Americas after identifying inefficiencies in conventional anaerobic digestion systems. From 2022–2025, I pursued a long-term independent research collaboration with Quasar Energy Group, with experimental validation conducted through industry and academic laboratories. The work combined laboratory testing, pilot-scale digester simulations, and computational modeling rather than a traditional internship format.

Research Mentor: Dr. Yebo Li (Chief Innovation and Science Officer) from Quasar Energy Group; yli@quasareg.com