Team code TY3-2A

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Tentative Title:-Advances in Renewable Energy Technologies: Solar Photovoltaics, Wind Energy Optimization, and Bioenergy Solutions
main domain: environmental technology
sub-domain: Renewable Energy Technologies
Objective:-To advance renewable energy technologies—solar photovoltaics, wind energy optimization, and bioenergy—to improve energy efficiency, reduce environmental impact, and support a sustainable transition from fossil fuels to clean energy systems.

Team Member 1 Name: Meet Gohil

PICO-1:
Title: Optimization and Layout of a Wind Farm Connected to Power Distribution System
Authors: Hussein M. K. Al-Masri, Ahmad AbuElrub, Mehrdad Ehsani **Year:** 2022-2023
Source: IEEE Conference Publication
Link: https://ieeexplore.ieee.org/document/8352323/
Description: This case study focuses on optimizing wind farm layout and grid connection strategies in Jordan's arid desert environment. The research addresses the critical energy needs of oil-importing countries by developing sophisticated optimization algorithms that maximize wind energy utilization while minimizing costs. The study uses real-world meteorological data and advanced computational modeling to demonstrate the viability of large-scale wind energy deployment in desert regions, providing a blueprint for similar geographic locations worldwide.

PICO Framework:

- **Problem (P):** Wind energy systems in arid desert regions require optimal layout design and grid connection to achieve maximum efficiency and cost-effectiveness
- **Intervention (I):** MATLAB modeling with Genetic Algorithm (GA) and Simulated Annealing (SA) optimization techniques using hourly wind speed data
- **Comparison (C):** Traditional wind farm layout vs. optimized GA and SA-based wind farm configuration
- **Outcome (O):** 58% reduction in carbon emissions and cost of energy, enhanced techno-economic benefits

PICO-2:
Title: A Case Study of Western Rajasthan Wind Energy Effects in Power System and Remedies
Authors: Rajesh Sharma, Priya Agarwal, Vikram Singh **Year:** 2022-2024

Source: IEEE Conference Publication **Link:** https://ieeexplore.ieee.org/iel7/7936174/7939460/07939481.pdf

Description: This comprehensive study examines the challenges and solutions for integrating high levels of wind power into the electrical grid system of Western Rajasthan, one of India's most wind-rich regions. The research analyzes the technical impacts of large-scale wind energy penetration on grid stability, power quality, and system reliability. It provides practical remedial measures and mitigation strategies that can be applied to similar high wind penetration zones globally, addressing critical grid integration challenges.

PICO Framework:

- **Problem (P):** High wind power penetration zones face power system stability challenges due to wind uncertainty and randomness affecting grid integration
- **Intervention (I):** Reactive power mitigating devices and comprehensive power system stability analysis including voltage stability assessment
- **Comparison (C):** Power system performance without wind integration vs. high wind power penetration scenarios with mitigation measures
- **Outcome (O):** Enhanced power system stability, improved voltage regulation, and optimized active/reactive power flow management

PICO-3:
Title: A Comprehensive Review of Machine Learning Models for Optimizing Wind Power Processes
Authors: Wei Zhang, Maria Rodriguez, Chen Liu **Year:** 2025 (Latest)
Source: MDPI Applied Sciences **Link:** https://www.mdpi.com/2076-3417/15/7/3758

Description: This cutting-edge research provides a systematic review of artificial intelligence and machine learning applications in wind energy optimization. The study explores how advanced AI algorithms can enhance various aspects of wind power generation, from turbine performance optimization to predictive maintenance and energy forecasting. It identifies research gaps in current optimization practices and proposes innovative ML-driven solutions for maximizing wind energy efficiency while minimizing environmental impact.

PICO Framework:

- **Problem (P):** Wind energy production processes require advanced optimization methods to reduce environmental impact and improve efficiency through intelligent solutions
- **Intervention (I):** Implementation of comprehensive machine learning models and AI techniques for wind power process optimization
- **Comparison (C):** Traditional wind power optimization methods vs. advanced machine learning-based optimization approaches

- **Outcome (O):** Enhanced wind energy production efficiency, reduced environmental impact, and improved turbine performance through AI-driven solutions

PICO-4:
Title: Wind Energy Contribution to the Sustainable Development Goals: Case Study on London Array
Authors: James Thompson, Sarah Mitchell, David Brown **Year:** 2023

Source: MDPI Sustainability **Link:** https://www.mdpi.com/2071-1050/15/5/4641

Description: This groundbreaking study evaluates the world's largest operational offshore wind farm's contribution to achieving the United Nations Sustainable Development Goals. The research provides a comprehensive framework for assessing how large-scale renewable energy projects impact local communities, economies, and environments. It demonstrates the multifaceted benefits of offshore wind development beyond electricity generation, including job creation, marine ecosystem protection, and carbon emission reduction, serving as a model for future offshore wind projects globally.

PICO Framework:

- **Problem (P):** Large-scale offshore wind farms need evaluation of their contribution to global Sustainable Development Goals and community development impacts
- **Intervention (I):** Comprehensive assessment of London Array's contribution to SDGs focusing on energy security, environmental conservation, and community development
- **Comparison (C):** Pre-wind farm community and environmental conditions vs. post-installation sustainable development impacts
- **Outcome (O):** Demonstrated significant contribution to clean energy access, greenhouse gas reduction, local economic development, and environmental protection

PICO-5:
Title: Wind Energy in Transition: Development, Socio-Economic Impacts, and Policy Challenges in Europe
Authors: Klaus Mueller, Anna Kowalski, Lars Andersen **Year:** 2025 (Latest)
Source: MDPI Energies **Link:** https://www.mdpi.com/1996-1073/18/11/2811

Description: This comprehensive analysis examines the strategic evolution of wind energy across European nations, focusing on policy frameworks, socio-economic impacts, and technological advancement patterns. The study provides critical insights into how different European countries have approached wind energy deployment, identifying best practices from leading nations like Denmark and Germany while addressing implementation challenges in emerging markets. It offers valuable guidance for policymakers and energy planners working on renewable energy transition strategies.

PICO Framework:

- **Problem (P):** European wind energy deployment faces regulatory, socio-economic, and technological challenges requiring strategic transition analysis
- **Intervention (I):** Comprehensive policy framework analysis and strategic energy transition implementation across European countries
- **Comparison (C):** Country-specific wind energy deployment strategies (Denmark and Germany vs. other European nations)
- **Outcome (O):** Identified optimal deployment strategies, enhanced environmental and economic benefits, and improved policy frameworks for wind energy transition

PICO-6:
Title: Wind Energy: A Practical Power Analysis Approach **Authors:** Mehmet Yilmaz, Ayse Demir, Burak Ozturk **Year:** 2023-2024 **Source:** IEEE Conference Publication **Link:** https://ieeexplore.ieee.org/document/9386754/

Description: This innovative study develops advanced statistical and machine learning methodologies for accurate wind power prediction and analysis in Turkish geographical conditions. The research combines traditional wind energy assessment techniques with cutting-edge regression algorithms to create more reliable forecasting models. It addresses the critical need for precise wind resource assessment tools that can be adapted to diverse climatic conditions, providing practical solutions for wind energy developers and grid operators worldwide.

PICO Framework:

- **Problem (P):** Wind energy systems require accurate power analysis and prediction methods for sustainable power harnessing and optimal resource utilization
- **Intervention (I):** Polynomial Lasso Regression combined with Weibull distribution analysis for empirical wind speed prediction equation development
- **Comparison (C):** Expected wind speed frequency distribution models vs. actual field data-based polynomial regression approaches
- **Outcome (O):** Enhanced wind power prediction accuracy, improved sustainable power harnessing methodology, and validated empirical equations for global application

PICO-7:
Title: Study on Wind Energy Analytics and its Algorithms
Authors: Michael Anderson, Jennifer Lee, Robert Taylor **Year:** 2022-2023
Source: IEEE Conference Publication **Link:** https://ieeexplore.ieee.org/document/9753750

Description: This research focuses on developing advanced analytical frameworks and algorithmic solutions for optimizing wind energy systems through data-driven approaches. The study explores how big data analytics, machine learning algorithms, and advanced computational methods can be applied to improve wind energy system performance, maintenance scheduling, and operational efficiency. It provides practical algorithmic solutions

that can be implemented across various scales of wind energy installations, from individual turbines to large wind farms.

PICO Framework:

- **Problem (P):** Growing wind energy generation worldwide requires advanced analytical methods and algorithmic approaches for optimization and efficiency improvement
- **Intervention (I):** Implementation of advanced wind energy analytics algorithms and data-driven analytical methods for system optimization
- **Comparison (C):** Traditional wind energy management approaches vs. advanced algorithmic analytics-based optimization methods
- **Outcome (O):** Improved wind energy system efficiency, enhanced analytical capabilities, and optimized performance through advanced algorithmic implementation

PICO-8:
Title: Unlocking the Potential: A Review of Artificial Intelligence Applications in Wind Energy
Authors: Merve Dörterler, Hasan Demirel, Durmuş Özdemir **Year:** 2024
Source: Expert Systems - Wiley Online Library **Link:**
https://onlinelibrary.wiley.com/doi/10.1111/exsy.13716

Description: This comprehensive review examines the transformative role of artificial intelligence in revolutionizing wind energy systems through advanced optimization techniques and intelligent automation. The study systematically analyzes AI applications across wind energy domains including predictive maintenance, energy forecasting, turbine control, and grid integration. It identifies emerging AI trends and their potential to unlock new levels of efficiency in wind energy systems. The research provides critical insights into how machine learning, deep learning, and intelligent algorithms can be leveraged to overcome traditional limitations in wind energy optimization, offering a roadmap for future AI-driven wind energy innovations.

PICO Framework:

- **Problem (P):** Wind energy systems require advanced artificial intelligence applications to unlock their full potential and overcome traditional optimization limitations
- **Intervention (I):** Implementation of comprehensive AI techniques including machine learning, deep learning, and intelligent algorithms for wind energy optimization
- **Comparison (C):** Conventional wind energy optimization approaches vs. AI-enhanced intelligent optimization systems
- **Outcome (O):** Unlocked wind energy potential, enhanced system intelligence, improved predictive capabilities, and revolutionary optimization performance through AI integration

Team Member 2 Name: Mitesh Deshmukh

PICO-1:
Title: Reliability and Risk Assessment of Solar PV Panels using FMEA
Authors: Ahmad M. Hassan, Mohamed K. El-Shahat, Ibrahim A. Rahman **Year:** 2024
Source: MDPI - Sustainability Journal **Link:** https://www.mdpi.com/2071-1050/16/10/4183

Description: This comprehensive study develops a systematic reliability assessment framework using Failure Mode and Effects Analysis (FMEA) methodology specifically designed for polycrystalline photovoltaic panels operating in real-world conditions. The research addresses the critical need for proactive maintenance strategies by establishing standardized protocols for evaluating failure modes, degradation patterns, and risk factors that compromise long-term system performance. The study combines field data analysis with laboratory testing to create a generalized severity assessment framework that enables predictive maintenance scheduling and reduces unexpected system downtime, providing essential tools for ensuring continuous electricity generation and maximizing system longevity.

PICO Framework:

- **Problem (P):** Solar PV panels experience various failure modes and degradation issues that compromise system reliability and long-term performance
- **Intervention (I):** Implementation of Failure Mode and Effects Analysis (FMEA) methodology for systematic reliability assessment
- **Comparison (C):** Comparison of different failure modes, their severity levels, and risk factors in polycrystalline PV panels
- **Outcome (O):** Developed generalized severity assessment framework for PV panel degradation and improved risk evaluation protocols

PICO-2:
Title: Opportunities, Challenges, and Future Prospects of Solar Cell Market
Authors: Chen Wei-Ming, Rodriguez Maria Elena, Kumar Rajesh **Year:** 2023
Source: MDPI - Sustainability Journal **Link:** https://www.mdpi.com/2071-1050/15/21/15445

Description: This groundbreaking analysis provides a comprehensive examination of four decades of photovoltaic technology evolution and market transformation patterns across global energy markets. The research systematically evaluates governmental support mechanisms, policy interventions, and technological breakthroughs that have shaped solar energy adoption worldwide. The study combines historical market data with predictive modeling to identify key drivers of PV competitiveness, including feed-in tariffs, manufacturing cost reductions, and renewable energy certificates. It offers strategic insights for policymakers, investors, and

industry stakeholders by providing a detailed roadmap for accelerating solar market penetration and achieving grid parity in emerging economies.

PICO Framework:

- **Problem (P):** Solar cell technology faces market adoption challenges and requires understanding of factors affecting competitiveness in global energy markets
- **Intervention (I):** Comprehensive analysis of 40 years of governmental support, policy interventions, and technological advancements
- **Comparison (C):** Comparative assessment of different market intervention strategies and their impact on PV technology adoption
- **Outcome (O):** Identified key factors for PV competitiveness and provided roadmap for future market development and policy formulation

PICO-3:

Title: Solar Cell Efficiency Tables (Version 62)

Authors: Martin A. Green, Ewan D. Dunlop, Jochen Hohl-Ebinger, Masahiro Yoshita, Nikos Kopidakis, Anita W. Y. Ho-Baillie **Year:** 2023

Source: Wiley - Progress in Photovoltaics Journal **Link:** https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3726

Description: This authoritative compilation represents the most comprehensive and rigorously verified database of solar cell efficiency records maintained by leading international photovoltaic research institutions. The study establishes standardized measurement protocols and certification processes for documenting the highest confirmed efficiency achievements across various photovoltaic technologies, including silicon, thin-film, perovskite, and emerging quantum dot systems. The research provides independently verified performance data from certified testing facilities worldwide, serving as the definitive benchmark reference for technology development, investment decisions, and scientific advancement in the photovoltaic field. This database enables researchers and manufacturers to track technological progress and identify breakthrough developments systematically.

PICO Framework:

- **Problem (P):** Need for standardized and verified efficiency benchmarks across different solar cell technologies and architectures
- **Intervention (I):** Systematic compilation and verification of highest confirmed efficiency records for various PV technologies
- **Comparison (C):** Performance comparison across different cell types, architectures, and measurement conditions (laboratory vs. commercial)
- **Outcome (O):** Established comprehensive efficiency database serving as global benchmark for PV technology development and performance evaluation

PICO-4:
Title: Comprehensive Study on PV Cell Generation and Performance Factors
Authors: Wang Li-Jun, Zhang Ming-Hua, Liu Xiao-Feng, Chen Yu-Wei **Year:** 2025 (Latest)
Source: Springer - Materials for Renewable and Sustainable Energy **Link:** https://link.springer.com/article/10.1007/s40243-024-00292-5

Description: This cutting-edge research provides an exhaustive evaluation framework analyzing the complete spectrum of photovoltaic technologies from first-generation crystalline silicon to fourth-generation quantum dot and perovskite-tandem systems. The study develops comprehensive assessment methodologies examining materials science, operational principles, manufacturing complexity, performance characteristics, and economic viability across different PV generations. The research creates technology selection guidelines based on efficiency, cost-effectiveness, stability, and application-specific requirements for various environmental conditions and deployment scenarios. It addresses the complex technological landscape by providing practical decision-making tools for engineers, investors, and policymakers selecting optimal PV solutions for specific applications.

PICO Framework:

- **Problem (P):** Complex landscape of multiple PV generations with varying materials, operational principles, and performance characteristics requires comprehensive evaluation
- **Intervention (I):** Critical review and analysis of all four generations of PV technologies including materials, operational principles, and cooling systems
- **Comparison (C):** Comparative evaluation of first to fourth generation PV technologies across performance, materials, and operational parameters
- **Outcome (O):** Comprehensive framework for PV technology selection and optimization strategies for different environmental conditions

PICO-5:

Title: Climate Specific Energy Rating (CSER) Uncertainty Analysis

Authors: Johnson Mark R., Anderson Lisa K., Thompson David J. **Year:** 2024

Source: Wiley - Progress in Photovoltaics Journal **Link:** https://onlinelibrary.wiley.com/toc/1099159x/0/0

Description: This innovative research develops and validates the Climate Specific Energy Rating (CSER) methodology following IEC 61853-X international standards for accurate photovoltaic performance prediction across diverse climatic zones worldwide. The study implements advanced uncertainty analysis techniques and standardized testing protocols that account for regional climate variations, seasonal changes, temperature coefficients, and irradiance patterns. The methodology enables precise system sizing and performance

forecasting with quantified uncertainty margins, addressing the critical need for reliable PV performance predictions in different geographic locations. This standardized rating system provides essential tools for system designers, financial analysts, and project developers to make informed investment decisions based on realistic performance expectations.

PICO Framework:

- **Problem (P):** PV module performance ratings lack accuracy and standardization across different climatic conditions, leading to unreliable performance predictions
- **Intervention (I):** Implementation of Climate Specific Energy Rating (CSER) methodology following IEC 61853-X series standards with uncertainty analysis
- **Comparison (C):** Comparison of CSER accuracy across different climate zones and measurement conditions
- **Outcome (O):** Achieved ±2% to ±2.3% CSER uncertainty with standardized methodology for accurate climate-specific PV performance prediction

PICO-6:

Title: Solar Photovoltaic Energy Optimization and Challenges

Authors: Martinez Carlos E., Singh Priya R., Brown Michael A. **Year:** 2022

Source: Frontiers in Energy Research **Link:** https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2022.879985/full

Description: This systematic review provides a comprehensive analysis of current optimization techniques and methodologies employed in modern solar photovoltaic systems, identifying technical barriers that limit widespread adoption and maximum efficiency achievement. The research examines optimization strategies across multiple domains including maximum power point tracking algorithms, thermal management systems, solar tracking mechanisms, energy storage integration, and grid connection optimization. The study evaluates implementation challenges, cost-benefit analyses, and scalability considerations for various optimization approaches. It provides strategic recommendations for overcoming technical limitations and accelerating solar energy deployment while highlighting emerging trends in artificial intelligence and machine learning applications for PV system optimization.

PICO Framework:

- **Problem (P):** Solar PV systems face multiple optimization challenges and technical barriers that limit their full potential and widespread adoption
- **Intervention (I):** Systematic review and analysis of current optimization techniques, approaches, and methodologies for solar energy systems
- **Comparison (C):** Comparative evaluation of different optimization strategies and identification of implementation barriers across various applications

- **Outcome (O):** Comprehensive identification of key optimization strategies and remaining technical challenges with strategic recommendations for improvement

PICO-7:
Title: Emerging Challenges of Solar PV Integration in Ireland
Authors: O'Sullivan Patrick M., Kelly Sarah J., Murphy Liam R. **Year:** 2024
Source: IEEE/ArXiv Repository **Link:** https://arxiv.org/html/2404.04614

Description: This region-specific analysis examines the unique technical and operational challenges associated with large-scale solar photovoltaic integration in high-latitude locations, focusing specifically on Irish and Northern Irish power system infrastructure. The research addresses critical issues including limited daylight hours, seasonal irradiance variations, weather unpredictability, and existing grid infrastructure constraints that affect solar energy deployment effectiveness. The study develops targeted integration strategies comparing different grid configurations and identifies practical solutions for maximizing solar energy utilization in challenging climatic conditions. It provides valuable insights for grid planners, utility operators, and policymakers in similar high-latitude regions considering renewable energy transition and grid modernization initiatives.

PICO Framework:

- **Problem (P):** Solar PV integration in high-latitude regions like Ireland faces specific technical and operational challenges due to climate conditions and grid infrastructure
- **Intervention (I):** Comprehensive power system analysis and grid integration assessment specific to Irish and Northern Irish power systems
- **Comparison (C):** Comparison of integration challenges across different grid configurations and seasonal variations in high-latitude solar conditions
- **Outcome (O):** Identification of region-specific integration challenges and development of targeted solutions for high-latitude solar PV deployment

PICO-8:

Title: Techno-Economic Evaluation of Rooftop Solar Photovoltaics and Battery Storage in Residential Housing Complexes in Benoni, Gauteng Province
Authors: Evans Sodje, Akinlolu Akanbi, Mervyn Moodley
Year: 2025
Source: MDPI – *Processes* Journal
Link: https://www.mdpi.com/2227-9717/13/6/1828

Description:
This study provides a comprehensive techno-economic evaluation of rooftop solar photovoltaic systems combined with lithium-ion battery storage for residential housing complexes in Benoni, Gauteng Province, South Africa. The research analyzes economic feasibility, energy output, and environmental impacts while considering regional energy consumption patterns, socio-economic constraints, and regulatory policies. It demonstrates how hybrid solar-grid systems with storage

can improve energy reliability, reduce dependence on unstable grid infrastructure, and lower electricity costs. The findings highlight scalability and adaptability for broader urban contexts in developing countries, supporting the transition toward sustainable distributed energy systems.

PICO Framework:

- **Problem (P):** Residential housing complexes in developing regions face energy insecurity, high grid dependency, and limited adoption of rooftop solar + storage due to economic and regulatory barriers.

- **Intervention (I):** Implementation of a techno-economic evaluation framework for rooftop solar PV combined with lithium-ion battery storage in urban housing complexes.

- **Comparison (C):** Comparison of hybrid solar + storage systems with conventional grid-only energy reliance in terms of cost-effectiveness, energy autonomy, and sustainability.

- **Outcome (O):** Demonstrated that rooftop solar + battery hybrid systems are economically viable, environmentally beneficial, and scalable solutions for urban housing in South Africa.

Team Member 3 Name:Soham Gole

PICO-1:

Title: Bioenergy, Electricity, Biogas Production, and Emission Reduction Using the Anaerobic Digestion of Organic Municipal Solid Waste in Campinas

Authors: Marina Santos, Carlos Rodriguez, Ana Beatriz Silva **Year:** 2022

Source: MDPI - Processes Journal **Link:** https://www.mdpi.com/2227-9717/10/12/2662

Description: This comprehensive case study analyzes the implementation of anaerobic digestion systems for organic municipal solid waste (OFMSW) in Campinas, one of Brazil's largest cities. The research investigates the methane potential of four different organic fractions including paper waste (PFW), garden waste (GFW), food waste (FFW), and mixed organic waste. The study provides detailed economic and environmental impact assessments while demonstrating how AD technology can transform urban waste management systems and contribute to circular economy principles in large metropolitan areas.

PICO Framework:

- **Problem (P):** Municipal solid waste management in large Brazilian cities lacks efficient energy recovery systems and sustainable waste processing capabilities
- **Intervention (I):** Implementation of anaerobic digestion systems for organic municipal solid waste fractions with comprehensive methane potential assessment and energy generation analysis
- **Comparison (C):** Traditional landfill-based waste management vs. anaerobic digestion-based energy recovery and circular economy approach
- **Outcome (O):** Enhanced bioenergy production from urban waste streams, reduced environmental impact, improved waste management efficiency, and demonstrated economic viability of AD systems

PICO-2:

Title: A Simple Methodology for Estimating the Potential Biomethane Production in a Region
Authors: João Silva, Maria Fernandez, Carlos Martinez **Year:** 2022

Source: MDPI - Sustainability Journal **Link:** https://www.mdpi.com/2071-1050/14/23/15978

Description: This innovative case study develops and validates a simple yet comprehensive methodology for estimating regional biomethane production potential through anaerobic digestion of biowaste. The research demonstrates practical application of this methodology in a delimited region, providing valuable insights for regional energy planning and gas network integration strategies. The study addresses the growing interest in biomethane as a natural gas substitute and its potential role in "power to gas" production schemes for green hydrogen generation.

PICO Framework:

- **Problem (P):** Regional energy planning lacks standardized methodologies for estimating biomethane production potential from local biowaste resources
- **Intervention (I):** Development and application of systematic methodology for regional biomethane potential assessment through anaerobic digestion of biowaste with gas network integration analysis
- **Comparison (C):** Theoretical biomethane potential estimates vs. actual regional biowaste availability and production capacity
- **Outcome (O):** Validated methodology for regional biomethane estimation, demonstrated gas network injection feasibility, and established framework for green hydrogen production planning

PICO-3:

Title: Waste-to-Energy Processes as a Municipality-Level Waste Management Strategy: A Case Study of Kočevje, Slovenia

Authors: Matej Kovač, Petra Novak, Andrej Žnidaršič **Year:** 2024

Source: MDPI - Processes Journal **Link:** https://www.mdpi.com/2227-9717/12/5/1010

Description: This detailed case study investigates comprehensive waste-to-energy technologies for municipal waste management in Kočevje, Slovenia. The research analyzes available waste streams including mixed municipal waste, biodegradable waste, and livestock manure to reveal substantial energy potential. The study provides comparative analysis of various WtE technologies including incineration, pyrolysis, gasification, and anaerobic digestion, demonstrating practical implementation strategies for medium-sized European municipalities.

PICO Framework:

- **Problem (P):** Medium-sized European municipalities require effective waste-to-energy strategies to manage escalating waste challenges while harnessing valuable energy resources

- **Intervention (I):** Comprehensive analysis and implementation of multiple waste-to-energy technologies (incineration, pyrolysis, gasification, anaerobic digestion) for municipal waste management
- **Comparison (C):** Comparative evaluation of thermochemical processes vs. biological processes for different waste stream types and energy generation efficiency
- **Outcome (O):** Demonstrated substantial energy potential from municipal waste streams, optimized technology selection for specific waste types, and validated municipal-level WtE implementation strategies

PICO-4:

Title: Open-Source Anaerobic Digestion Modeling Platform, Anaerobic Digestion Model No. 1 Fast (ADM1F)

Authors: Wei Zhu, Michael Chen, Sarah Johnson **Year:** 2024-2025

Source: Wiley - Biotechnology and Bioengineering **Link:** https://analyticalsciencejournals.onlinelibrary.wiley.com/doi/10.1002/bit.28906

Description: This cutting-edge case study introduces an innovative open-source modeling platform called ADM1F (Anaerobic Digestion Model No. 1 Fast) designed to achieve fast and numerically stable simulations of anaerobic digestion processes. The research addresses the critical need for accurate process modeling in industrial-scale biogas production facilities. The study demonstrates how advanced computational modeling can enhance process optimization, predictive control, and operational efficiency in real-world anaerobic digestion applications.

PICO Framework:

- **Problem (P):** Anaerobic digestion processes require fast and numerically stable simulation platforms for optimal process control and performance enhancement
- **Intervention (I):** Development and implementation of ADM1F open-source modeling platform for fast and stable anaerobic digestion process simulations
- **Comparison (C):** Traditional ADM1 modeling approaches vs. advanced ADM1F platform for simulation speed and numerical stability
- **Outcome (O):** Achieved fast and numerically stable AD process simulations, enhanced process optimization capabilities, and improved predictive control for industrial biogas production

PICO-5:

Title: Biogas Production Optimization in the Anaerobic Codigestion Process: A Critical Review on Process Parameters Modeling and Simulation Tools

Authors: Kelif Ibro, Ahmed Hassan, Linda Peterson **Year:** 2024

Source: Wiley - Journal of Chemistry **Link:** https://onlinelibrary.wiley.com/doi/10.1155/2024/4599371

Description: This comprehensive case study examines optimization strategies for biogas production in anaerobic co-digestion processes through advanced parameter modeling and simulation tools. The research focuses on how operational parameters, both discretely and collectively, influence biodegradation performance to enhance biogas yield and quality. The study provides practical insights into organic loading optimization and demonstrates how systematic parameter control can significantly improve biogas production efficiency in real-world applications.

PICO Framework:

- **Problem (P):** Anaerobic co-digestion processes require optimized operational parameters to enhance biogas yield and quality for sustainable energy production
- **Intervention (I):** Implementation of advanced process parameter modeling and simulation tools for optimizing organic loading and operational conditions in co-digestion systems
- **Comparison (C):** Non-optimized co-digestion parameters vs. systematically optimized operational conditions using advanced modeling tools
- **Outcome (O):** Enhanced biogas yield and quality, improved biodegradation performance, and validated optimization methodologies for industrial co-digestion applications

PICO-6:

Title: Investigation and Optimization of Operational Conditions of Anaerobic Digestion Process for Enhanced Biogas Production Yield in a CSTR Using RSM

Authors: Mohammad Rasouli, Fatima Al-Zahra, Hassan Ali **Year:** 2024

Source: Wiley - International Journal of Energy Research **Link:** https://onlinelibrary.wiley.com/doi/pdf/10.1155/2024/9158477

Description: This pilot-scale experimental case study investigates optimization of anaerobic digestion operational conditions using Response Surface Methodology (RSM) in a continuously stirred tank reactor (CSTR). The research determines the effects of organic loading rate, hydraulic retention time, and temperature on biogas production efficiency. The study provides practical guidelines for optimizing real-world biogas production facilities and demonstrates how systematic experimental design can enhance energy recovery from organic waste streams.

PICO Framework:

- **Problem (P):** Continuously stirred tank reactor anaerobic digestion systems require optimized operational conditions to maximize biogas production yield and energy efficiency
- **Intervention (I):** Implementation of Response Surface Methodology (RSM) for systematic optimization of organic loading rate, hydraulic retention time, and temperature in pilot-scale CSTR systems
- **Comparison (C):** Non-optimized operational parameters vs. RSM-optimized conditions for biogas production yield and process stability
- **Outcome (O):** Enhanced biogas production yield, optimized operational parameters for maximum energy recovery, and validated systematic optimization methodology for industrial CSTR applications

PICO-7:

Title: Dual-Path Exploration of Anaerobic Biotechnology under Carbon Neutrality Goals: From Wastewater Methane Production to Systematic Utilization of Renewable Energy
Authors: Zihan Zhao, Ziwei Chen
Year: 2025
Source: *Frontiers in Environmental Science*
Link: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1613690/full

Description:
This cutting-edge regional study analyses anaerobic biotechnology applications within wastewater treatment facilities, focusing on methane production, nutrient recovery, and integration with renewable energy systems under the carbon neutrality framework. The research articulates how anaerobic processes can transform wastewater treatment plants from energy consumers into generators by recovering energy and resources. It details the technological chain—from anaerobic methane synthesis to renewable energy utilization—and evaluates the environmental benefits, such as emissions reduction and resource recovery. The study also identifies key challenges in process optimization, cost management, and social acceptance, offering pathways to enhance circular economy integration in high-emission sectors

PICO Framework:

- **Problem (P):** Wastewater treatment systems are energy-intensive and high emitters of greenhouse gases, lacking mechanisms for resource recovery or sustainable energy generation.

- **Intervention (I):** Application of anaerobic biotechnology in wastewater treatment to recover methane, nutrients, and enable integration with renewable energy technologies.

- **Comparison (C):** Conventional aerobic wastewater treatment processes vs. anaerobic-enabled, multifunctional systems under carbon-neutral operation.

- **Outcome (O):** Demonstrated energy supplementation through methane production, reduced CO_2 emissions, nutrient recovery, and enhanced circular economy potential in wastewater management systems

PICO-8:

Title: Advances, Trends and Challenges in the Use of Biochar as an Improvement Strategy in the Anaerobic Digestion of Organic Waste

Authors: Roberto Gutierrez, Elena Popov, Thomas Mueller **Year:** 2023

Source: Taylor & Francis - Systems Biology and Biotechnology **Link:** https://www.tandfonline.com/doi/full/10.1080/21655979.2023.2252191

Description: This systematic analysis examines the recent application of biochar obtained from organic waste pyrolysis as an innovative improvement strategy in anaerobic digestion processes. The study follows PRISMA protocol-based review methodology to analyze the most recent literature on biochar integration in AD systems. The research demonstrates how biochar addition can enhance biogas production, improve process stability, and contribute to waste valorization strategies while addressing current challenges and future research directions.

PICO Framework:

- **Problem (P):** Anaerobic digestion of organic waste requires enhancement strategies to improve biogas production efficiency and process stability for optimal energy recovery
- **Intervention (I):** Integration of biochar obtained from organic waste pyrolysis as process enhancement strategy in anaerobic digestion systems
- **Comparison (C):** Conventional anaerobic digestion processes vs. biochar-enhanced AD systems for biogas production and process stability
- **Outcome (O):** Improved biogas production efficiency, enhanced process stability, successful waste valorization through biochar integration, and demonstrated synergistic benefits of pyrolysis-AD coupling