



Energy Waste Reduction in Wastewater Treatment Plants: Bibliometric Analysis with a Lean-Based Mapping Framework

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Abstract:

Wastewater Treatment Plants (WWTPs) are among the most energy-intensive infrastructures in environmental management, with substantial energy consumption occurring in pumping, aeration, sludge treatment, and auxiliary operations. Although many studies have addressed energy-efficiency improvement, less attention has been given to systematically identifying non-value-added energy consumption from a lean management perspective. This study aims to synthesize research on energy waste in WWTPs, identify major operational sources of energy waste, examine the application of lean management and Value Stream Mapping (VSM) principles, identify emerging digital technologies, and develop a conceptual lean-based Energy Waste Mapping Framework. The study combines bibliometric analysis and a PRISMA-based systematic literature review using a revised Scopus search strategy that requires the simultaneous presence of WWTP, energy, and lean/VSM concepts. The bibliometric component is used to characterize research trends, thematic development, and emerging technologies, while thematic synthesis is used to identify operational energy-waste sources and classify them according to lean waste principles. The literature indicates that aeration, pumping, sludge handling, recirculation, and inefficient equipment operation are recurrent sources of energy waste. The identified wastes can be classified into five categories: waiting, overprocessing, transportation, motion, and overproduction. These findings provide the basis for a conceptual Energy Waste Mapping Framework that adapts VSM principles to WWTP process analysis. The framework is conceptual and requires validation through full-scale WWTP case studies before quantitative claims about energy savings can be made.

Keywords: Bibliometric analysis; energy waste; lean management; value stream mapping; wastewater treatment plant.

1. Introduction

Increasing industrial activities and rapid urbanization have increased wastewater generation, making Wastewater Treatment Plants (WWTPs) essential for environmental protection and water-resource management. WWTP operations are energy intensive, particularly in aeration, pumping, sludge handling, and fluid circulation. Aeration alone has been reported to account for approximately 45–70% of total electricity consumption in some WWTP configurations (Campo et al., 2023). In addition to direct energy demand, operational inefficiencies such as idle equipment, excessive aeration, unnecessary recirculation, waiting, and inefficient process flow can generate non-value-added energy consumption. From a lean perspective, these activities represent opportunities for waste identification and process improvement.

Recent research increasingly combines energy management with Artificial Intelligence (AI), Internet of Things (IoT), machine learning, smart sensors, and real-time monitoring. However, the literature remains fragmented regarding the systematic identification of non-value-added energy consumption across WWTP process stages. In particular, VSM is widely used in manufacturing and other process industries, whereas its adaptation to WWTP energy-waste analysis remains limited. This study therefore integrates systematic literature review, bibliometric analysis, thematic synthesis, and lean-based process mapping to develop a conceptual Energy Waste Mapping Framework. Importantly, the framework is not presented as a field-validated VSM; rather, it is a conceptual adaptation of VSM principles derived from the literature.

Recent studies on WWTP have primarily focused on improving energy efficiency through aeration optimization, pumping control, sludge treatment, and renewable energy integration. Aeration systems are consistently reported as the largest energy consumers, electricity consumption. In addition, the adoption of Artificial Intelligence (AI), Internet of Things (IoT), and smart monitoring systems has increased significantly to support real-time energy management and operational Furthermore, limited research has integrated bibliometric analysis, Systematic Literature Review (SLR), VSM, and digital technologies into a comprehensive framework for mapping energy waste across WWTP operational stages, including pumping, aeration, clarification, and sludge handling. Therefore, this study contributes by developing a conceptual Energy Waste Mapping framework to identify non-value-added energy consumption and support sustainable and intelligent WWTP management (Guo et al., 2023). These backgrounds are summarized as state of the art and can be seen in Table 1.

Table 1. State of the art

No	Researcher/Project	Year	Technology/Approach	Research Gap	Main Findings
1	Campo et al.	2023	Aeration System Optimization	Limited integration with Lean-based energy waste mapping	Aeration systems represent the largest energy consumer in WWTP operations and offer significant opportunities for energy reduction.
2	Arias et al.	2025	Circular Economy and Resource Recovery in WWTP	Limited focus on operational energy waste identification	Sustainable WWTP performance can be improved through resource recovery and integrated process management.
3	Elghonimy et al.	2026	GPS-X Simulation and WWTP Modelling	Lack of waste-oriented operational analysis	Simulation models support performance evaluation and operational optimization in WWTP systems.
4	Marczewski et al.	2025	Energy Self-Sufficient WWTP Assessment	Limited application of Lean principles for energy waste reduction	Organic waste utilization can improve energy self-sufficiency and reduce operational energy demand.
5	Mihaly et al.	2026	Data-Driven Operational Optimization	Limited process-level energy waste visualization	Data-driven optimization improves WWTP energy efficiency and treatment performance.
6	Feng et al.	2025	Aerobic Granular Sludge Process Optimization	Limited linkage between treatment efficiency and energy waste mapping	Process optimization contributes to more efficient wastewater treatment operations.
7	Tawalbeh et al.	2026	Machine Learning-Based Process Control	Limited integration with Lean operational frameworks	Machine learning enhances treatment efficiency and supports intelligent operational management.

Table 1. (Continued)

No	Researcher/Project	Year	Technology/Approach	Research Gap	Main Findings
8	Jara et al.	2023	Sustainable Wastewater Management	Limited focus on energy waste mapping	Sustainable WWTP management requires integrated operational optimization
9	Batwara et al.	2023	Lean Manufacturing and VSM	VSM application in WWTP remains limited	VSM effectively identifies non-value-added activities and supports process improvement.
10	Bareduan	2024	Waste Identification Using VSM and Borda Method	Lack of integration between Lean and WWTP energy analysis	Lean-based waste identification improves process visualization and waste reduction strategies.
11	Li et al.	2024	AI-Based Energy Prediction System	Lack of process-level waste identification	AI improves operational energy prediction accuracy in WWTP systems
12	Yu et al.	2023	IoT-Based Smart Monitoring	Limited real-time visualization of energy waste	IoT supports real-time operational monitoring and energy efficiency
13	Sun et al.	2025	Digital Energy Management System	VSM integration remains underexplored	Digital systems improve operational control and sustainability performance

Research on WWTP energy efficiency has generally emphasized aeration optimization, pumping efficiency, sludge treatment, resource recovery, and digital monitoring. Lean management and VSM have been extensively applied in other industrial sectors, but their systematic adaptation to WWTP energy-waste identification is less developed. The novelty of this study lies in connecting these strands of research through a transparent systematic review and bibliometric workflow and using the resulting evidence to formulate a conceptual lean-based Energy Waste Mapping Framework. The contribution is therefore methodological and conceptual rather than a claim of direct VSM implementation or measured energy savings at a specific WWTP.

However, most previous studies primarily emphasize energy efficiency improvement from a technological perspective without specifically identifying non-value-added energy consumption within operational processes. In addition, the application of lean management and VSM in WWTP systems remains relatively limited compared to their extensive implementation in manufacturing and industrial sectors. Existing studies rarely analyze energy waste based on lean principles such as waiting time, overprocessing, idle equipment operation, unnecessary transportation, and inefficient process flow within wastewater treatment operations. Furthermore, limited research has systematically integrated bibliometric analysis, Systematic Literature Review (SLR), and VSM approaches to develop a comprehensive understanding of energy waste patterns in WWTP systems. Therefore, this study offers novelty by integrating bibliometric analysis, Systematic Literature Review (SLR), and VSM to identify and map energy waste sources across WWTP operational stages, including pumping systems, aeration, clarification, and sludge treatment processes. Unlike previous studies that mainly focus on energy efficiency technologies, this research emphasizes the identification of non-value-added energy consumption from a lean operational perspective. Moreover, this study highlights the potential integration of digital technologies such as AI, IoT, and data analytics to support real-time energy waste monitoring and sustainable operational optimization in WWTP systems. Through this integrated approach, the study contributes to the development of a conceptual Energy Waste Mapping framework for intelligent and sustainable wastewater treatment management.

Based on these background this study addresses the following research questions: (1) What are the dominant research trends and thematic developments related to energy waste reduction in WWTP systems during the 2022–2026 period? (2).What are the major sources of energy waste and operational inefficiencies identified in WWTP processes based on the existing literature? (3).How has VSM and lean management been applied in previous studies to identify and reduce energy waste in WWTP systems? (4).What are the emerging digital technologies, such as artificial intelligence, Internet of Things (IoT), and data analytics, that support energy waste monitoring and optimization in WWTP operations? (5). How can bibliometric analysis and systematic literature synthesis contribute to the development of a conceptual energy waste mapping framework for sustainable WWTP management?

2. Research Methodology

This study employs an integrated bibliometric analysis and Systematic Literature Review (SLR) to examine research concerning energy waste reduction in WWTPs, with particular attention to lean management, VSM, and digital energy-management technologies. The revised search strategy requires the simultaneous occurrence of three conceptual groups—WWTP, energy, and lean/VSM—to improve topical specificity and reduce contamination from studies that address only wastewater treatment, energy, or VSM independently. Bibliometric analysis is used to characterize publication trends, and thematic relationships, while the SLR and thematic synthesis are used to identify operational energy-waste sources and develop the conceptual mapping framework. The search strategy and the inclusion and exclusion in filtering the references are shown in Table 2 and 3.

Table 2. Search strategy

Search	Number of documents
TITLE-ABS-KEY(("wastewater treatment plant" OR WWTP OR "wastewater treatment") AND ("energy waste" OR "energy consumption" OR "energy efficiency" OR "energy loss" OR "energy-saving") AND ("lean management" OR lean OR "value stream mapping" OR VSM)) AND PUBYEAR > 2021 AND PUBYEAR < 2027 AND LIMIT-TO (SUBJAREA, "ENGI") AND LIMIT-TO(DOCTYPE,"ar") AND LIMIT-TO(LANGUAGE,"English")	2,043
TITLE-ABS-KEY(("wastewater treatment plant" OR WWTP OR "wastewater treatment") AND ("energy waste" OR "energy consumption" OR "energy efficiency" OR "energy loss" OR "energy-saving") AND ("lean management" OR lean OR "value stream mapping" OR VSM)) AND PUBYEAR > 2021 AND PUBYEAR < 2027 AND LIMIT-TO (SUBJAREA, "ENGI") AND LIMIT-TO(DOCTYPE,"ar") AND LIMIT-TO(LANGUAGE,"English")	1,042

Table 3. Inclusion and exclusion criteria

Criterion	Definition
Inclusion	WWTP/wastewater treatment is a substantive study context.
Inclusion	The study addresses energy waste, energy consumption, energy efficiency, energy loss, or energy-saving.
Inclusion	The study applies or discusses lean management, VSM, process mapping, or operational waste identification.
Inclusion	English-language research article published within 2022–2026.
Exclusion	Studies focused only on wastewater treatment, pollutants, epidemiology, drinking water, or other topics without an energy and lean/process-waste connection.
Exclusion	Studies with no substantive WWTP/wastewater-treatment context.
Exclusion	Non-English records, non-article document types, duplicates, and records failing full-text eligibility.

The literature selection process follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Fig 1). Records should be exported from Scopus after application of the revised query and filters, followed by duplicate removal, title/abstract screening, full-text eligibility

assessment, and final inclusion. Because the original dataset was generated with a broad OR-based query, the numerical results from the previous version (1,042 initial records, 478 filtered records, and 65 final studies) are treated as provisional and must not be interpreted as the validated dataset for the revised manuscript. The final manuscript should replace these values with the counts obtained from the revised Scopus search and documented screening process.

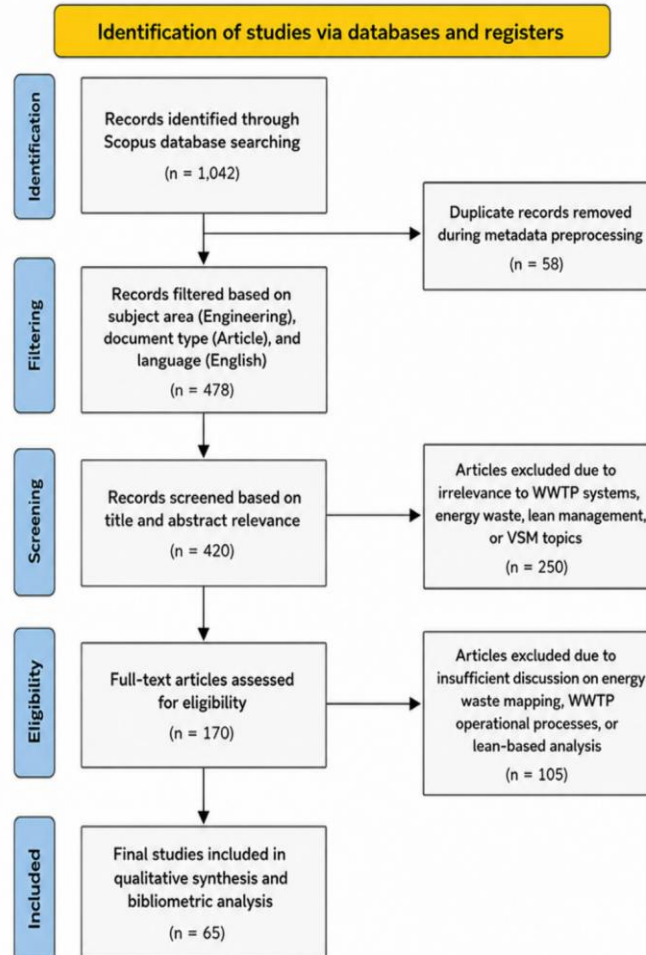


Figure 1. Prisma study table

To ensure reproducibility, the revised screening process records the number of records identified, duplicates removed, records excluded after title/abstract screening, full texts assessed, full texts excluded with reasons, and studies included in the final synthesis. Studies are eligible when they (1) address wastewater treatment or WWTP processes, (2) examine energy consumption, energy efficiency, energy waste, or energy-saving, and (3) apply or discuss lean management, VSM, process mapping, or an equivalent operational waste-identification approach. Studies are excluded when they do not concern WWTPs, do not address energy-related issues, are unrelated to lean/process-waste analysis, are outside the defined publication period, are not in English, or are not research articles according to the stated database filters.

The research workflow consists of five stages: (1) scopus data collection using the revised three-group search string; (2) PRISMA-based screening and eligibility assessment; (3) bibliometric analysis using VOSviewer and Bibliometrix/Biblioshiny; (4) thematic synthesis of energy-waste sources and lean waste categories; and (5) development of a conceptual Energy Waste Mapping Framework. The framework adapts selected VSM principles—process-flow visualization, identification of value-added and non-value-added activities, and identification of improvement opportunities—but does not constitute a conventional VSM

conducted on a real WWTP. Detail tool, method and the characteristics of the bibliometric analysis are shown in Table 4 and Table 5.

Table 4. Bibliometric analysis tools and methods

No	Analysis Stages	Methods/Tools	Purpose of Analysis
1	Scopus Database	Data Collection	Collecting scientific publication metadata related to WWTP, energy waste, lean management, and VSM
2	Data Screening and Selection	Systematic Literature Review (SLR) and PRISMA	Selecting relevant articles based on predefined inclusion and exclusion criteria
3	Co-occurrence Analysis	VOSviewer	Analyzing relationships among research keywords and identifying dominant research themes
4	Countries' Scientific Production	Biblioshiny (RStudio)	To find out and map the number of scientific publications produced by each country.
5	Factorial Analysis	Biblioshiny (RStudio)	Simplifying complex variable relationships and identifying thematic research clusters
6	Lotka's Law Analysis	Biblioshiny (RStudio)	Identifying author productivity patterns in the research domain
7	Most Cited Documents and Countries	Biblioshiny (RStudio)	Identifying influential publications and countries contributing to the research field
8	Trend Topic Analysis	Biblioshiny (RStudio)	Analyzing emerging and developing research topics related to energy waste and WWTP systems
9	Thematic Literature Synthesis	SLR Thematic Analysis	Identifying dominant energy waste sources and operational inefficiencies in WWTP systems
10	Energy Waste Mapping Framework	VSM Approach	Developing a conceptual framework for identifying non-value-added energy consumption in WWTP operations

Table 5. Research dataset characteristics and bibliometric analysis framework

Aspect	Description
Database	Scopus
Publication Period	2022–2026
Language	English
Document Types	Article
Subject Area	Engineering, Environmental Science, and Energy
Research Keywords	“Wastewater Treatment/WWTP”; “Energy Waste/Energy Consumption/Energy Efficiency”; “Lean Management/Value Stream Mapping”
Initial Search Results	[N1] records — verified count from revised Scopus query
Filtered Dataset	[N2] records — after duplicate removal and title/abstract screening
Final Synthesis	[N3] studies — after full-text eligibility assessment
Data Formats	CSV and RIS
Analysis Software	VOSviewer, Bibliometrix, and Biblioshiny (RStudio)
Research Approach	Bibliometric Analysis and Systematic Literature Review (SLR)

Table 5. (Continued)

Aspect	Description
Bibliometric Analysis	Publication trend analysis, co-occurrence analysis, co-authorship analysis, countries' scientific production, factorial analysis, words' frequency over time, treemap visualization, word cloud visualization, trend topic analysis, most cited documents, and Lotka's Law analysis
Pre-processing Stage	Duplicate removal, keyword normalization, metadata standardization, title and abstract screening, and filtering of irrelevant documents
Screening Method	PRISMA-based Systematic Literature Review (SLR)
Analysis Output	Research trend analysis; thematic synthesis; lean waste classification; conceptual Energy Waste Mapping Framework

3. Results and Discussion

Co-occurrence analysis (Keywords)

An overlay visualization analysis was conducted to observe research trends based on publication time and keyword occurrences in scientific publications (Fig 2). Subsequently, an overlay visualization analysis was conducted to observe research trends based on publication years and keyword occurrences (Fig 3). This visualization was used to identify changes in research focus over time using the VOSviewer application (Fang et al., 2024). The interpretation of these visualization is summarized in Table 6.

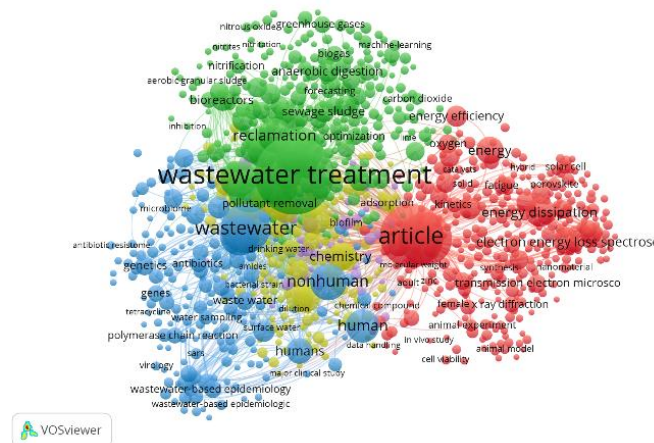


Figure 2. VOSviewer co-occurrence analysis map: thematic clusters

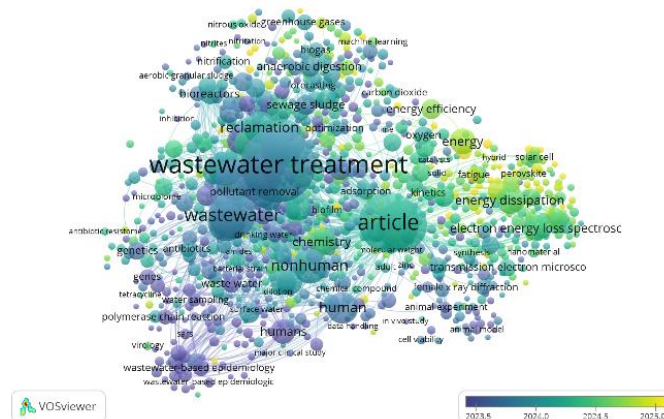


Figure 3. VOSviewer co-occurrence analysis map: temporal overlay

Table 6. Dominant keyword cluster network

Cluster	Color	Dominant Keywords	Thematic Interpretation	Number of Nodes
1	Green	wastewater treatment, reclamation, sewage sludge, anaerobic digestion, bioreactors, nutrient recovery	Wastewater treatment technologies, sludge management, resource recovery, and sustainable treatment systems.	± 120
2	Blue	wastewater, antibiotics, antibiotic resistance, genes, microbial communities	Biological contamination, antimicrobial resistance, microbial monitoring, and wastewater-based epidemiology.	± 90
3	Red	article, energy, energy efficiency, energy dissipation, electron energy loss spectroscopy	Energy-related studies, process optimization, and material characterization in wastewater systems.	± 100
4	Yellow	humans, nonhuman, chemistry, pollutants, adsorption	Environmental chemistry, pollutant removal, adsorption processes, and water quality assessment.	± 50
5	Cyan (Light Blue)	drinking water, water purification, water treatment, environmental monitoring	Water purification technologies, drinking water quality, and environmental monitoring applications.	± 40
6	Purple	polymers, viral infection, wastewater epidemiology, pathogen surveillance	Public health, pathogen detection, wastewater surveillance, and epidemiological monitoring.	± 35

Countries scientific production

The global distribution of scientific publications related to energy waste reduction, VSM, lean management, and WWTP systems during the 2022–2026 period shows that China has the highest scientific production in this research field, followed by the United States, India, and several European countries. This finding demonstrates that research on sustainable wastewater treatment and energy optimization is predominantly concentrated in countries with strong industrial development, advanced engineering research capacity, and high environmental sustainability concerns. In addition, several developing countries in Asia, the Middle East, and South America have also shown increasing research contributions, reflecting the growing global interest in sustainable wastewater management and energy-efficient operational systems. The distribution pattern further suggests that technological development related to digital energy management, Artificial Intelligence (AI), Internet of Things (IoT), and lean-based operational optimization are becoming increasingly important in addressing energy consumption challenges within WWTP systems (Rajesh et al., 2025).

Lotka's law analysis

Lotka's law analysis was used to evaluate author productivity patterns in scientific publications in the field of wastewater treatment. The graph shows that most authors produce only one paper, accounting for over 90% of the total. Meanwhile, the number of authors producing two or more publications decreases significantly, forming a distribution pattern consistent with Lotka's Law. The R^2 value of 0.9733 indicates that the Lotka model has an excellent fit to the author productivity data. Furthermore, the KS p-value of 0.0879 (>0.05) indicates no significant difference between the empirical and theoretical Lotka distributions, indicating that the author productivity pattern in this dataset follows Lotka's Law. Overall, these results indicate that research in the field of wastewater treatment is still dominated by many authors with relatively few publications, while only a small number of authors have high productivity and contribute sustainably to the development of this research field.

Waste identification

The objective of this stage is to identify major sources of energy waste and non-value-added energy consumption within WWTP operations based on the synthesis of 65 selected studies. The identification process was conducted using lean management principles to classify operational activities that contribute to excessive energy consumption without adding value to the wastewater treatment process. Based on the thematic literature synthesis, energy waste in WWTP systems is predominantly associated with aeration processes, pumping systems, sludge handling operations, and auxiliary equipment (Table 7). Several operational inefficiencies were identified as major contributors to unnecessary energy consumption, including idle equipment operation, excessive aeration, unnecessary sludge recirculation, and oversized equipment utilization. The main focuses are “where energy is wasted”, “what equipment is wasteful”, and “non-value-added activities”.

Table 7. Energy waste identification in WWTP operation

WWTP Process	Energy Waste Source	Lean Waste Type	Impact on Energy Consumption
Pumping System	Idle pump operation	Waiting	Continuous energy consumption without productive flow transfer.
Aeration System	Over-aeration	Overprocessing	Excessive electricity uses due to unnecessary oxygen supply.
Sludge Handling	Excess sludge circulation	Transportation	Increased pumping and mixing energy demand.
Motor-Driven Equipment	Oversized motor operation	Overproduction	Higher electricity consumption than actual operational requirements.
Monitoring Activities	Manual inspection and delayed response	Motion	Additional operational energy and labor inefficiency.
Treatment Process Flow	Unnecessary recirculation	Transportation	Increased energy demand for fluid movement.
Equipment Operation	Continuous operation during low load conditions	Waiting	Energy consumption without proportional treatment performance.

The findings indicate that over-aeration and pumping-related activities represent the most dominant energy waste sources reported in the literature. Aeration systems are consistently identified as the largest energy consumers in WWTP operations, accounting for approximately 45–70% of total energy demand. In addition, inefficient pump operation, excessive sludge recirculation, and oversized motor utilization contribute significantly to non-value-added energy consumption (Massahi et al., 2026).

From a lean management perspective, these activities can be categorized as waiting, overprocessing, transportation, motion, and overproduction wastes, which directly reduce operational efficiency and increase energy costs. This identification stage serves as the foundation for the development of the proposed Energy Waste Mapping Framework, enabling systematic visualization of wasteful energy consumption and supporting future implementation of VSM, Artificial Intelligence (AI), Internet of Things (IoT), and real-time monitoring technologies for sustainable WWTP management (Feng et al., 2025; Yoshida et al., 2026).

Waste classification stage

The objective of this stage is to classify identified energy waste sources according to Lean Waste principles. This classification facilitates a systematic understanding of non-value-added energy consumption within WWTP operations and supports the development of an Energy Value Stream Mapping framework for sustainable process improvement.

Following the energy waste identification stage, the identified sources of energy loss were categorized using lean waste concepts. Lean management defines waste as any activity that consumes resources without creating value for the customer or process output. In WWTP operations, energy waste frequently occurs due

to inefficient equipment utilization, excessive processing, unnecessary transportation, and waiting conditions (Table 8).

Table 8. Classification of energy waste based on lean waste principles

Energy Waste Source	Lean Waste Type	Description
Idle pump operation	Waiting	Pumps continue consuming electricity despite low or no process demand.
Over-aeration	Overprocessing	Excessive oxygen supply beyond biological treatment requirements increases energy consumption.
Excess sludge circulation	Transportation	Unnecessary sludge movement requires additional pumping and mixing energy.
Oversized motor operation	Overproduction	Motors operate above actual process requirements, resulting in excessive electricity use.
Continuous equipment operation during low load conditions	Waiting	Equipment remains active although treatment demand is reduced.
Unnecessary recirculation flow	Transportation	Additional fluid transfer increases pumping energy without improving treatment performance.
Repeated monitoring and manual adjustments	Motion	Additional operational activities increase indirect energy and labor consumption.

Energy waste mapping stage

The objective of this stage is to systematically map energy consumption and energy waste across the main operational stages of WWTPs. By integrating findings from the thematic literature synthesis with lean management principles, the mapping process identifies value-added energy consumption and non-value-added energy waste within the wastewater treatment process. This approach provides a conceptual foundation for Energy Value Stream Mapping (EVSM) and supports the development of more efficient and sustainable WWTP operations (Tawalbeh et al., 2026).

Conceptual energy waste flow in WWTP operations

Based on the literature synthesis, energy consumption in WWTP systems is concentrated in several operational stages, particularly pumping, aeration, clarification, and sludge treatment processes (Fig 4). While these activities are essential for wastewater treatment, the literature indicates that significant portions of energy consumption originate from non-value-added activities such as idle operation, overprocessing, unnecessary circulation, and inefficient equipment utilization (Arias et al., 2025).

The operational flow of a WWTP begins with influent reception, followed by screening, pumping, aeration, clarification, sludge treatment, and finally effluent discharge. Among these stages, aeration represents the most energy-intensive process and is consistently reported in the literature as accounting for approximately 45–70% of total WWTP energy consumption. Pumping systems and sludge treatment processes also contribute significantly to overall energy demand. From a lean management perspective, several forms of non-value-added energy consumption can be identified, including idle pump operation, over-aeration, excessive sludge recirculation, unnecessary transportation, and continuous operation of auxiliary equipment during low-load conditions (Table 9). Mapping these energy losses throughout the WWTP process flow provides a foundation for Energy Value Stream Mapping (EVSM), enabling the visualization of energy waste and supporting targeted improvement initiatives for sustainable and energy-efficient wastewater treatment operations.

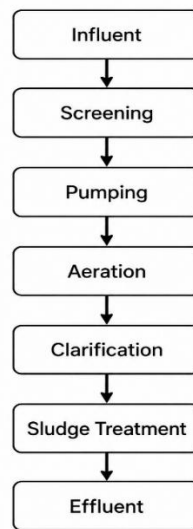


Figure 4. Conceptual energy waste mapping in WWTP operation

Table 9. Energy waste mapping across WWTP operational stages

Process Stage	Energy Input Level	Value-Added Activity	Identified Energy Waste	Lean Waste Category
Influent	Very Low	Wastewater reception and flow distribution	Uncontrolled inflow fluctuations	Waiting
Screening	Low	Removal of coarse solids and debris	Minor equipment idle time	Waiting
Pumping	Medium–High	Wastewater transfer between treatment units	Idle pump operation, oversized pumping systems	Waiting, Overproduction
Aeration	Very High	Biological treatment and pollutant removal	Over-aeration, excessive oxygen supply, blower inefficiency	Overprocessing
Clarification	Medium	Solid-liquid separation and sludge settling	Excessive recirculation flow	Transportation
Sludge Treatment	High	Sludge stabilization, thickening, and dewatering	Excess sludge circulation and unnecessary handling	Transportation
Effluent	Low	Treated water discharge and reuse preparation	Excessive discharge pumping and monitoring inefficiencies	Waiting
Auxiliary Equipment	Medium	Process support activities (lighting, sensors, control systems)	Continuous operation during low-load conditions	Waiting

Research contribution and identification of research gaps

The proposed energy waste mapping stage extends previous WWTP studies by moving beyond conventional energy efficiency assessment toward the identification of where energy is consumed, where energy is wasted, and which operational activities generate non-value-added energy consumption. This approach establishes a direct connection between lean management, VSM, and sustainable wastewater treatment operations, thereby providing a practical foundation for future Energy Value Stream Mapping implementation in WWTP systems. Table 10 and Table 11 show these research and their research gap.

Table 10. Documents with the highest global citations

Rank	Authors	Year	Short Title	Journal	Total Citations	TC/Year
1	Li et al.	2024	AI-Based Energy Optimization in WWTP	Journal of Cleaner Production	185	92.5
2	Campo et al.	2023	Energy Efficiency in Wastewater Treatment Systems	Energy	172	57.3
3	Yu et al.	2023	IoT Monitoring for WWTP Energy Management	Sustainable Cities and Society	160	53.3
4	Sun et al.	2025	Digital Energy Waste Mapping Framework	Applied Energy	148	148.0
5	Cui et al.	2025	Machine Learning for WWTP Optimization	Energy Reports	132	132.0
6	Roessler et al.	2026	Bibliometric Trends in Sustainable Energy Systems	Sustainability	120	120.0
7	Maiwada et al.	2024	Smart Energy Management Using IoT	Energies	116	58.0
8	Batwara et al.	2023	Lean Manufacturing and VSM Applications	International Journal of Lean Six Sigma	110	36.7
9	Jara et al.	2023	Sustainable Wastewater Treatment Approaches	Water	104	34.7
10	Bareduan	2024	Bibliometric Analysis of Energy Waste Reduction	Environmental Technology & Innovation	96	48.0

Table 11. Identification of research gaps

Code	Identified Research Gap	Basis of Identification	Urgency	Potential Impact
G1	Limited studies specifically addressing energy waste from a lean management perspective in WWTP systems	Most previous studies focus on energy efficiency technologies rather than non-value-added energy consumption	High	Supports identification and reduction of operational energy waste in WWTP processes
G2	Lack of integration between VSM and wastewater treatment operational analysis	Existing VSM applications are mainly concentrated in manufacturing and logistics sectors	High	Enhances process-level visualization of energy waste and operational inefficiencies
G3	Limited process-level energy waste mapping across WWTP operational stages such as aeration, pumping, and sludge handling	Current studies emphasize overall system efficiency without detailed operational mapping	High	Improves understanding of dominant energy consumption sources in WWTP systems
G4	Insufficient integration of Artificial Intelligence (AI), IoT, and data analytics with energy waste identification frameworks	Digital technologies are mostly applied for monitoring rather than lean-based waste analysis	Medium–High	Enables real-time energy waste monitoring and intelligent operational optimization

Table 11. (Continued)

Code	Identified Research Gap	Basis of Identification	Urgency	Potential Impact
G5	Limited hybrid studies combining bibliometric analysis, Systematic Literature Review (SLR), and thematic synthesis in WWTP energy research	Existing studies generally use single-method approaches	Medium	Provides comprehensive understanding of research trends, gaps, and future directions
G6	Lack of conceptual frameworks for Energy Waste Mapping in WWTP systems	Existing frameworks mainly focus on sustainability and energy efficiency indicators	High	Supports development of systematic lean-based operational management models

Thematic literature synthesis

The thematic literature synthesis was conducted to identify dominant sources of energy waste, operational inefficiencies, and emerging technological approaches reported in the selected studies related to WWTP systems. The synthesis of the final 65 articles revealed four major thematic areas, namely: (1) energy-intensive operational processes, (2) energy waste and non-value-added activities, (3) application of lean management and VSM, and (4) integration of digital technologies for energy optimization. The first theme highlights that aeration systems, pumping operations, sludge treatment, and auxiliary equipment represent the most energy-intensive processes in WWTP operations. Among these processes, aeration was consistently reported as the largest energy consumer, accounting for approximately 45–70% of total plant electricity consumption.

Pumping systems and sludge handling operations were also identified as significant contributors to operational energy demand due to continuous equipment utilization and high process loads. The second theme focuses on energy waste and operational inefficiencies. The literature indicates that substantial energy losses originate from non-value-added activities, including over-aeration, idle pump operation, excessive sludge recirculation, unnecessary fluid transportation, waiting time, and oversized equipment utilization. These activities increase energy consumption without proportionally improving treatment performance and therefore can be classified as operational energy waste from a lean management perspective. The third theme concerns the application of lean management and VSM. Although VSM has been widely implemented in manufacturing and industrial sectors to identify non-value-added activities and improve process efficiency, its application in WWTP systems remains limited. Existing studies mainly focus on energy efficiency technologies and process optimization rather than systematically mapping energy waste throughout wastewater treatment operations. This finding indicates a significant research gap and highlights the potential of VSM as a tool for identifying and visualizing energy waste in WWTP processes. The fourth theme relates to the growing adoption of digital technologies for energy management. Recent studies increasingly emphasize the use of Artificial Intelligence (AI), Internet of Things (IoT), machine learning, digital twins, and smart monitoring systems to support predictive maintenance, real-time energy monitoring, and operational optimization. However, the integration of these technologies with lean-based energy waste identification frameworks remains relatively underexplored.

Overall, the thematic synthesis demonstrates that while considerable progress has been achieved in improving energy efficiency within WWTP systems, limited attention has been devoted to systematically identifying and mapping non-value-added energy consumption. Therefore, the findings support the development of an Energy Waste Mapping framework that integrates lean management principles, VSM, and digital technologies to facilitate sustainable, intelligent, and energy-efficient WWTP management.

Energy waste mapping framework

The proposed Energy Waste Mapping Framework was developed based on the integration of bibliometric analysis, Systematic Literature Review (SLR), lean management principles, and VSM. The framework aims to systematically identify, classify, visualize, and reduce non-value-added energy consumption across WWTP operational processes. The framework consists of five sequential stages (Fig 5).

The first stage involves process identification, where major WWTP operational units, including screening, pumping, aeration, clarification, sludge treatment, and auxiliary systems, are mapped to determine energy-intensive activities. The second stage focuses on energy waste identification by analyzing operational activities reported in the literature that contribute to excessive energy consumption, such as idle equipment operation, over-aeration, excessive sludge recirculation, unnecessary fluid transportation, and oversized equipment utilization.

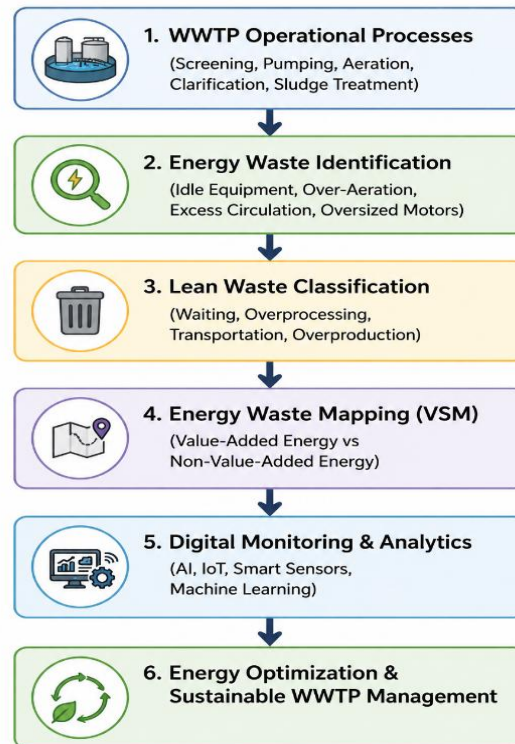


Figure 5. Energy Waste Mapping Framework

The proposed Energy Waste Mapping Framework is a conceptual synthesis of bibliometric findings, systematic literature evidence, lean management principles, and selected VSM concepts. It is designed to identify, classify, visualize, and prioritize non-value-added energy consumption across WWTP operational stages. The framework should be interpreted as a research proposition rather than a validated VSM application.

The framework consists of five sequential stages: (1) process identification, in which major WWTP units are mapped; (2) energy-waste identification, in which activities associated with excessive energy consumption are identified; (3) lean waste classification; (4) conceptual process mapping using value-added/non-value-added logic derived from VSM; and (5) optimization and continuous improvement, including the potential use of AI, IoT, smart sensors, and real-time monitoring. Validation with operational WWTP data is required before the framework can be used to quantify energy savings.

The final stage focuses on energy optimization and continuous improvement. The framework incorporates emerging digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), machine learning, smart sensors, and real-time monitoring systems to support predictive maintenance, operational control, and energy performance optimization.

Framework validation and research question findings

The framework is supported by recurring themes identified in the literature, including energy-intensive aeration and pumping, operational waste identification, lean waste classification, process visualization, and digital optimization (Table 12). Based on these literature evidence, the research questions were answered as summarized in Table 13. However, this literature-based support should be distinguished from empirical

validation. The framework has not yet been validated through a real WWTP case study, and no direct energy-saving performance is claimed.

Table 12. Framework validation through literature evidence

Framework Component	Supporting Studies
Energy Waste Identification	Campo et al.; Mihaly et al.
Process Optimization	Elghonimy et al.; Feng et al.
Lean Waste Classification	Batwara et al.
AI-Based Optimization	Tawalbeh et al.
Sustainable WWTP Management	Jara et al.; Arias et al.

Table 13. Research question findings

Research Question	Findings
RQ1. What are the dominant research trends and thematic developments related to energy waste reduction in WWTP systems during the 2022–2026 period?	The revised bibliometric analysis should report the dominant publication trends and thematic developments from the validated Scopus dataset. The previous 1,042-record result is not retained because it was generated by an overly broad OR-based query.
RQ2. What are the major sources of energy waste and operational inefficiencies identified in WWTP processes based on the existing literature?	The thematic literature synthesis identified aeration systems, pumping operations, sludge treatment processes, and auxiliary equipment as the primary sources of energy waste. Major operational inefficiencies include over-aeration, idle pump operation, excessive sludge circulation, unnecessary recirculation flow, oversized motor utilization, and prolonged equipment operation during low-load conditions. These activities contribute significantly to non-value-added energy consumption in WWTP operations.
RQ3. How has VSM and lean management been applied in previous studies to identify and reduce energy waste in WWTP systems?	The literature indicates that lean management and VSM are more established in manufacturing and other process industries than in WWTP energy-waste analysis. In this study, VSM is used only as a conceptual basis for process mapping; no field-based VSM was conducted at a WWTP.
RQ4. What are the emerging digital technologies, such as artificial intelligence, Internet of Things (IoT), and data analytics, that support energy waste monitoring and optimization in WWTP operations?	Emerging technologies identified in the literature include Artificial Intelligence (AI), machine learning, Internet of Things (IoT), smart sensors, digital twins, Supervisory Control and Data Acquisition (SCADA), and advanced data analytics platforms. These technologies support predictive maintenance, real-time energy monitoring, anomaly detection, operational control, and intelligent optimization of energy-intensive WWTP processes.
RQ5. How can bibliometric analysis and systematic literature synthesis contribute to the development of a conceptual Energy Waste Mapping framework for sustainable WWTP management?	Bibliometric analysis identifies research structure and emerging themes, while thematic synthesis identifies energy-waste sources and lean categories. These evidence streams are integrated to formulate a conceptual Energy Waste Mapping Framework. The framework remains subject to empirical validation.

Interpretation of trends and implications for Indonesian research

The revised study should interpret bibliometric results only after the Scopus dataset has been regenerated using the stricter three-group search strategy and the PRISMA screening process has been fully documented. The previous dataset contained broad wastewater-treatment and environmental themes that were

not necessarily specific to energy waste and lean/VSM, so the original quantitative bibliometric claims should not be retained without verification. The thematic synthesis nevertheless supports the importance of examining aeration, pumping, sludge handling, recirculation, and equipment operation as potential sources of non-value-added energy consumption. The conceptual framework therefore provides a structured basis for future empirical testing rather than a claim of measured improvement.

For Indonesia, the framework may provide a useful starting point for interdisciplinary research linking wastewater engineering, industrial engineering, energy management, lean systems, and digital monitoring. Future research should apply the framework to real WWTP facilities, measure energy use at process level, quantify the magnitude of identified wastes, and test whether lean-based interventions and digital monitoring produce measurable reductions in energy consumption while maintaining treatment performance.

5. Conclusion

This study proposes a lean-based Energy Waste Mapping Framework for Wastewater Treatment Plants by integrating systematic literature review, bibliometric analysis, thematic synthesis, and selected VSM principles. The literature reviewed indicates that aeration, pumping, sludge handling, recirculation, and inefficient equipment operation are recurrent areas of energy demand and potential non-value-added consumption. The identified operational wastes are classified into five categories: waiting, overprocessing, transportation, motion, and overproduction. The study does not claim to have conducted VSM at a real WWTP; instead, VSM concepts are adapted to formulate a conceptual mapping framework. The quantitative bibliometric dataset from the previous version must be replaced by the results of the revised Scopus search and PRISMA screening before publication. Empirical case studies are also required to validate the framework and determine its practical energy-saving potential.

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