ISNN 3030-3907

2026/4
VOLUME 3

DEVELOPMENT OF SCIENCE

ILMIY JURNAL



Development of science

Ilmiy jurnal

2026/4 VOLUME 3

ISSN 3030 -3907

Ilmiy jurnal OAK rayosatining 2024 yil 27 sentabrdagi 361-son qaroriga asosan 02.00.00 kimyo fanlari hamda 2025 yil 12 fevral 367- son qaroriga asosan 05.00.00 texnika fanlari bo‘yicha falsafa doktori (PhD) va fan doktori (DSc) ilmiy darajasiga talabgorlarning dissertatsiya ishlari yuzasidan dissertatsiyalari asosiy ilmiy natijalarini chop etish tavsiya etilgan milliy ilmiy nashrlar ro‘yxatiga kiritilgan.

BOSH MUHARRIR:
Temirov Alisher Hoshim o‘g‘li – texnika fanlari falsafa doktori (PhD),Dotsent.
TAHRIRIYAT KENGASH RAISI:
Fozilov Sadriddin Fayzullayevich – texnika fanlari doktori, professor
TAHRIRIYAT KENGASH A’ZOLARI

TEXNIKA FANLARI/ TECHNICAL SCIENCES/ ТЕХНИЧЕСКИЕ НАУКИ

Bozorov G‘ayrat Rashidovich
Buxoro Davlat Texnika Universiteti, professor
Abdurahmonov Olim Rustamovich
Buxoro Davlat Texnika Universiteti, professor
Adizov Bobur Zamirovich
O‘zbekiston Respublikasi Fanlar akademiyasi Umumiy va noorganik kimyo instituti, professor
Hayitov Ruslan Rustamjonovich
Buxoro Davlat Texnika Universiteti, professor
Jumayev Qayum Karimovich
Buxoro Davlat Texnika Universiteti, professor.
Berdiyev Dorob Murodovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor
Maxmudov Rafiq Amonovich
Buxoro Davlat Texnika Universiteti, professor.
Tilloyev Lochin Ismatilloyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Raxmonov Qahramon Sanakulovich
Buxoro Davlat Texnika Universiteti, dotsent.
Barakayev Nusratullo Rajabovich
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti, professor.
Jo‘rayev Xayrullo Fayziyevich
Buxoro Davlat Texnika Universiteti, professor.
Panoyev Erali Rajabboyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Ataullayev Sherzod Nabiullyevich
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Malik Negmurodovich
Buxoro Davlat Texnika Universiteti, dotsent.
Axmedova Ozoda Bahronovna
Islom Karimov nomidagi Toshkent Davlat Texnika Universiteti.
Safarov Bahri Jumayevich
Buxoro Davlat Texnika Universiteti, dotsent.
Xaydarov Axtam Amonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Safarov Jasur Alijon o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.
Асадова Раъно Дилмуратовна
Тошкент Давлат техника университети доценти

KIMYO FANLARI/ CHEMICAL SCIENCES/ ХИМИЧЕСКИЕ НАУКИ

Axmedov Voxid Nizomovich
Buxoro Davlat Texnika Universiteti, professor
Umarov Baqo Bafoyevich
Buxoro Davlat Universiteti, professor
Kodirov Abduaxad Abduraximovich
Qarshi davlat Universiteti, professor
Qurbonov Mingniqul Jumagulovich
Qarshi davlat Universiteti, dotsent
Turemuratov Sharibay Naurizbaevich
O‘zbekiston Respublikasi Fanlar akademiyasi Qoraqalpog‘iston bo‘limi Bosh ilmiy kotibi, professor
Tursunov Kaxor Shonazarovich
Qarshi davlat Universiteti, professor
Do‘stov Hamro
Buxoro Davlat Texnika Universiteti, professor
Panoyev Nodir Shavkatovich
Buxoro Davlat Texnika Universiteti, dotsent.
Olimov Bobur Bahodir o‘g‘li
Buxoro Davlat Texnika Universiteti, dotsent.
Kasimov Sherzod Abduazimovich
Termiz Davlat Universiteti, professor.
Aliqulov Rustam Valiyevich
Termiz Davlat Universiteti, professor
Tropov Xamza Tursunovich
Samarqand Davlat Universiteti, professor

IQTISODIYOT FANLARI/ ECONOMICS/ ЭКОНОМИЧЕСКИЕ НАУКИ

Nizamov Aslitdin Badreddinovich
Buxoro Davlat Texnika Universiteti, professor.
Boboyev Akmal Choriyevich
Buxoro Davlat Texnika Universiteti, professor.
Ergashxojayeva Shaxnoza Djasurovna
Toshkent davlat iqtisodiyot universiteti, professor
Saidaxmedova Nodira Ilxomovna
Toshkent davlat iqtisodiyot universiteti, professor
Muxsinov Bekzod Toxirovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shakarov Qulmat Ashirovich
Renessans ta'lim universiteti,dotsent.
Jumaeva Zulfiya Qayumovna
Buxoro Davlat Texnika Universiteti, dotsent.
Norova Salomat Yusupovna
Buxoro Davlat Texnika Universiteti, dotsent.
Avezova Shaxnoza Maxmudjonovna
Buxoro Davlat Texnika Universiteti, dotsent.
Jalilov Jamshid G‘anijonovich
Toshkent davlat iqtisodiyot universiteti, dotsent
Xasanova Gulruh Djumanazarovna
Buxoro Davlat Texnika Universiteti, dotsent.

PEDAGOGIKA FANLARI/ PEDAGOGICAL SCIENCES / ПЕДАГОГИЧЕСКИЕ НАУКИ

Siddiqova Sadoqat G‘afforovna
Buxoro Davlat Texnika Universiteti, dotsent.
Zoyirov Erkin Xalilovich
Buxoro Davlat Texnika Universiteti, DSc, professor
Gaffarov Feruz Hasanovich
Puchon Universiteti, *professor*
Ruziyev Davron Yuldashevich
Buxoro Davlat Universiteti, professor
Muradova Firuza Rashidovna
Buxoro Davlat Texnika Universiteti, professor.
Yunusova Gulandon Samiyevna
Buxoro Davlat Texnika Universiteti, professor.
To‘xtayeva Zebo Sharifovna
Buxoro Davlat Texnika Universiteti, professor.
Navro‘zova Gulchixra Nigmatovna
Buxoro Davlat Texnika Universiteti, dotsent.
Uzoqova Laylo Polvonovna
Buxoro muhandislik – texnologiya instituti, dotsent.
To‘raqulova Marjona Qiyom qizi
Buxoro Davlat Texnika Universiteti, dotsent.
Muradova Zarina Rashidovna
Buxoro Davlat Texnika Universiteti, dotsent.
Murodov Sanjar Aslonovich
Buxoro Davlat Texnika Universiteti, dotsent.
Shodiyev Jahongir Jo‘raqulovich
Buxoro Davlat Texnika Universiteti, dotsent
Gaffarov Laziz Hasanovich
Buxoro muhandislik – texnologiya instituti, dotsent.

Tahririyat a’zolarning to‘liq ro‘yxati jurnalning www.devos.uz saytida keltirilgan.

Tahririyat hay’ati a’zolarining tarkibini o‘zgartirish hamda qo‘shimcha kiritish yoki tahririyat a’zoligidan chiqarish bosh muharrir tomonidan amalga oshiriladi.

ISSN 3030-3907

Development of science ilmiy jurnali 2024 yil 15 aprel kuni №256445 sonli guvohnoma bilan Davlat ro‘yxatidan o‘tgan.

To‘plam elektron ko‘rinishda (pdf formatida) mualliflarga taqdim etiladi. To‘plamga kiritiladigan maqolalarning mazmuni, ulardagi statistik ma’lumotlar va me’yoriy hujjatlarning to‘g‘riligiga hamda har qanday fikr - mulohazalarga mualliflarning o‘zlari mas’ul hisoblanadilar. Talablarga javob bermaydigan maqolalar to‘plamga kiritilmaydi. Tashkiliy qo‘mita maqola matnini qisqartirish, qisman tuzatish kiritish, seksiyalarga joylashtirish huquqiga ega.

ISSN 3030-3907

AUTOMATIC CONTROL SYSTEMS FOR ACTIVATED SLUDGE CONCENTRATION TO IMPROVE ENERGY EFFICIENCY IN WASTEWATER TREATMENT: A BIBLIOMETRIC REVIEW

Misliboyev Dilshod Abdumalikovich
National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers", PhD, Researcher,
E-mail: misliboyevdilshod@gmail.com
Pirimov Odil Jurayevich
National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers", Professor, DSc,
E-mail: pirimovo@mail.ru
Hakimov Pahlavon Qahramon o'g'li
"Bukhara State Technical University", PhD, Researcher,
E-mail: pakhlavonh@gmail.com

Annotation. Biological wastewater treatment plants are among the most energy-intensive components of agro-industrial infrastructure. Controlling the concentration of activated sludge is critical for maintaining purification quality and reducing the energy consumption of pumping systems. Objective: This article presents a comprehensive bibliometric review of automatic control systems used in wastewater treatment, with a specific focus on optimizing energy efficiency and process stability in secondary clarifiers. Methods: A systematic literature search was conducted using the Scopus database to retrieve relevant publications. The extracted data was then analyzed and visualized using VOSviewer and the Biblioshiny package to map the evolution of control strategies in this field. Results: The bibliometric analysis tracks the transition from traditional PID controllers to advanced Artificial Intelligence and Fuzzy Logic frameworks. The review identifies key research trends, highly cited authors, and critical gaps in the current literature regarding the digitization of recirculation loops. Conclusion: This review provides a strategic framework for implementing "Smart Water Management" systems in agro-industrial enterprises and highlights future directions for developing hybrid energy-saving control algorithms. This article investigates the enhancement of energy efficiency through the automatic control of activated sludge concentration in the biological wastewater treatment processes of agro-industrial complexes (AIC). Currently, biological treatment plants are among the most energy-intensive components of AIC infrastructure, with electricity costs accounting for 30% to 50% of total operational expenses.

Keywords: Activated sludge, automatic control, energy efficiency, wastewater treatment, agro-industry, digital technology, secondary clarifier, return activated sludge (RAS), PID-regulator.

Annotatsiya. Biologik oqova suvlarni tozalash inshootlari agro-sanoat infratuzilmasining eng ko'p energiya sarflaydigan qismlaridan biridir. Tozalash

ISSN 3030-3907

sifatini saqlash va nasos tizimlarining energiya sarfini kamaytirishda faol loy konsentratsiyasini nazorat qilish juda muhimdir. Maqsad: Ushbu maqolada oqova suvlarni tozalashda qo'llaniladigan avtomatik boshqaruv tizimlarining har tomonlama bibliometrik tahlili taqdim etilgan. Asosiy e'tibor ikkilamchi tindirgichlarda energiya samaradorligini optimallashtirish va jarayon barqarorligiga qaratilgan. Metodlar: Scopus ma'lumotlar bazasidan foydalangan holda adabiyotlarning tizimli qidiruvi o'tkazildi. Olingan ma'lumotlar VOSviewer va Biblioshiny paketi yordamida tahlil qilindi va ushbu sohadagi boshqaruv strategiyalari rivojlanishini ko'rsatish uchun vizuallashtirildi. Natijalar: Bibliometrik tahlil an'anaviy PID-regulyatorlardan ilg'or Sun'iy Intellekt va Noaniq mantiq (Fuzzy Logic) tizimlariga o'tishni ko'rsatadi. Sharhda asosiy tadqiqot yo'nalishlari, eng ko'p iqtibos keltirilgan mualliflar va resirkulyatsiya tizimlarini raqamlashtirishdagi bo'shliqlar aniqlangan. Xulosa: Ushbu sharh agro-sanoat korxonalarida "Aqlli suv boshqaruvi" (Smart Water Management) tizimlarini joriy etish uchun strategik asos bo'lib xizmat qiladi va gibrid energiya tejovchi boshqaruv algoritmlarini ishlab chiqishning istiqbolli yo'nalishlarini belgilab beradi.

Kalit so'zlar: Faol loy, avtomatik boshqaruv, energiya samaradorligi, oqova suvlarni tozalash, agro-sanoat, raqamli texnologiyalar, ikkilamchi tindirgich, qaytariluvchi faol loy (RAS), PID-regulyator.

Аннотация. Биологические очистные сооружения являются одними из наиболее энергоемких компонентов агропромышленной инфраструктуры. Контроль концентрации активного ила имеет решающее значение для поддержания качества очистки и снижения энергопотребления насосных систем. Цель: В данной статье представлен всесторонний библиометрический обзор систем автоматического управления, используемых при очистке сточных вод, с особым акцентом на оптимизацию энергоэффективности и стабильности процессов во вторичных отстойниках. Методы: Систематический поиск литературы проводился с использованием базы данных Scopus. Извлеченные данные были проанализированы и визуализированы с помощью VOSviewer и пакета Biblioshiny для отображения эволюции стратегий управления в этой области. Результаты: Библиометрический анализ отслеживает переход от традиционных ПИД-регуляторов к передовым системам искусственного интеллекта и нечеткой логики. В обзоре выявлены ключевые направления исследований, наиболее цитируемые авторы и критические пробелы в цифровизации контуров рециркуляции. Вывод: Данный обзор обеспечивает стратегическую основу для внедрения систем "Smart Water Management" на агропромышленных

ISSN 3030-3907

предприятиях и определяет будущие направления разработки гибридных энергосберегающих алгоритмов управления.

Ключевые слова: Активный ил, автоматическое управление, энергоэффективность, очистка сточных вод, агропромышленный комплекс, цифровые технологии, вторичный отстойник, возвратный активный ил (RAS), ПИД-регулятор.

1. INTRODUCTION.

At the global scale, the growing scarcity of water resources and the intensification of environmental challenges have positioned wastewater treatment and recycling within agro-industrial complexes (AIC) as a primary strategic necessity. Wastewater generated by AIC enterprises, particularly food processing facilities, is characterized by high concentrations of organic pollutants. Biological treatment, where activated sludge plays a pivotal role, remains the most effective method for purifying these effluents.

However, biological treatment plants are among the most energy-intensive components of agro-industrial infrastructure. Research indicates that electricity consumption accounts for 30% to 50% of the total operational costs of these facilities. The fundamental principles of energy-saving electrotechnologies and renewable energy integration within agro-industrial complexes, which are essential for addressing these challenges, have been extensively established in the foundational works of A.R. Radjabov (Radjabov, 2012; Radjabov, 2016; Radjabov, 2018). Currently, many local processing facilities manage activated sludge concentration through manual interventions or stationary control modes. This often leads to significant deviations in sludge concentration from optimal technological parameters, resulting in either a decline in treatment quality or excessive energy waste by the pumping systems. Furthermore, instability in the sludge concentration adversely affects the dissolved oxygen balance in aeration tanks, thereby reducing the overall process efficiency.

In recent years, the scientific community has increasingly focused on automated and energy-efficient control of wastewater treatment processes. For example, recent studies in 2026 highlight the shift towards advanced control systems, such as automated multi-chemical dosing using machine learning in aquaculture wastewater. Furthermore, adaptive PID controllers have been successfully deployed in fluid transmission networks, including wastewater pipelines, demonstrating the ability to maintain output stability within ±5%. Recent advancements have also introduced highly complex machine learning frameworks, such as Cyclic Residual-Steered Bayesian optimization, to dynamically manage aeration and chemical dosing under fluctuating influent conditions (Chen et al.,

ISSN 3030-3907

2026). Furthermore, the application of advanced graph models, microprocessor technologies, and the integration of artificial intelligence offer robust methodological solutions for optimizing linear stationary systems with variable delays, which is a common issue in wastewater pumping automation (Pirimov, 2020; Pirimov, 2021; Pirimov, 2024).

While these recent innovations confirm that automation is essential for system stability, there remains a critical research gap. Previous studies have heavily focused on chemical dosing, inline power generation, or aeration optimization. There remains a critical need for robust, easily implementable control strategies such as PID automation or Fuzzy Logic to optimize the overall energy balance by digitizing the secondary clarifier and recirculation loops. To address this gap, this review aims to analyze the current landscape of automatic control systems for activated sludge, serving as a critical step toward the implementation of "Smart Water Management" systems within the agro-industrial sector.

2. MATERIALS AND METHODS

2.1. Search Strategy and Database Selection To ensure a high-quality and comprehensive review of the current literature, a systematic search strategy was designed and executed. The Scopus database was selected as the primary source for data collection due to its extensive coverage of peer-reviewed engineering, environmental science, and automation technology journals. The literature search was conducted using a specific combination of keywords to capture all relevant publications. The primary search query applied to the "Article title, Abstract, Keywords" fields was: *"PID control in wastewater"*.

2.2. Inclusion and Exclusion Criteria To maintain the focus and quality of the bibliometric review, specific inclusion and exclusion criteria were applied to the initial search results. The inclusion criteria were defined as follows: (1) documents must focus on the automation or control of wastewater treatment processes; (2) the literature must be published in peer-reviewed journals or highly regarded international conference proceedings; and (3) the documents must be written in the English language to ensure accurate bibliometric processing. Documents that were strictly theoretical without application to wastewater, or published in non-indexed sources, were excluded. After applying these criteria, a final dataset of 74 highly relevant documents was obtained.

2.3. Data Extraction Once the final 74 documents were identified, the metadata of these articles were exported directly from the Scopus database. To ensure that no critical information was lost during the transfer process, the data was exported in the BibTeX (.bib) format. The extracted dataset comprehensively included citation information (author names, document titles, publication years,

ISSN 3030-3907

citation counts), bibliographical information (affiliations, publishers), and text analytics data (abstracts and author keywords). This comprehensive extraction provided the necessary foundation for deep bibliometric mapping.

2.4. Bibliometric Analysis and Visualization Tools The quantitative analysis and visual mapping of the extracted dataset were performed using two specialized software tools: VOSviewer and Biblioshiny.

- **Network Visualization:** VOSviewer software (version 1.6.20) was utilized to construct and visualize the keyword co-occurrence networks. To capture a detailed and granular map of the research field, the minimum number of keyword occurrences was adjusted to a low threshold, allowing the software to identify both dominant clusters (e.g., traditional PID controllers) and emerging sub-trends (e.g., Machine Learning optimization). Fractional counting was applied to normalize the strength of the links between keywords.
- **Scientific Production and Impact Metrics:** The Biblioshiny web interface, powered by the *bibliometrix* package in RStudio, was employed to analyze the global scientific production, trend topic networks, and citation metrics. The mapchart.net was specifically used to extract the highest-cited documents and generate geographical distribution maps to identify the regions driving innovation in activated sludge automation.

3. RESULT AND DISCUSSION

3.1. Bibliometric Network Analysis To understand the evolution of automatic control in wastewater treatment, a keyword co-occurrence network was generated based on the documents retrieved from Scopus. As illustrated in Figure 1, the bibliometric map reveals the primary clusters of research and identifies the most frequently discussed technologies in the field.

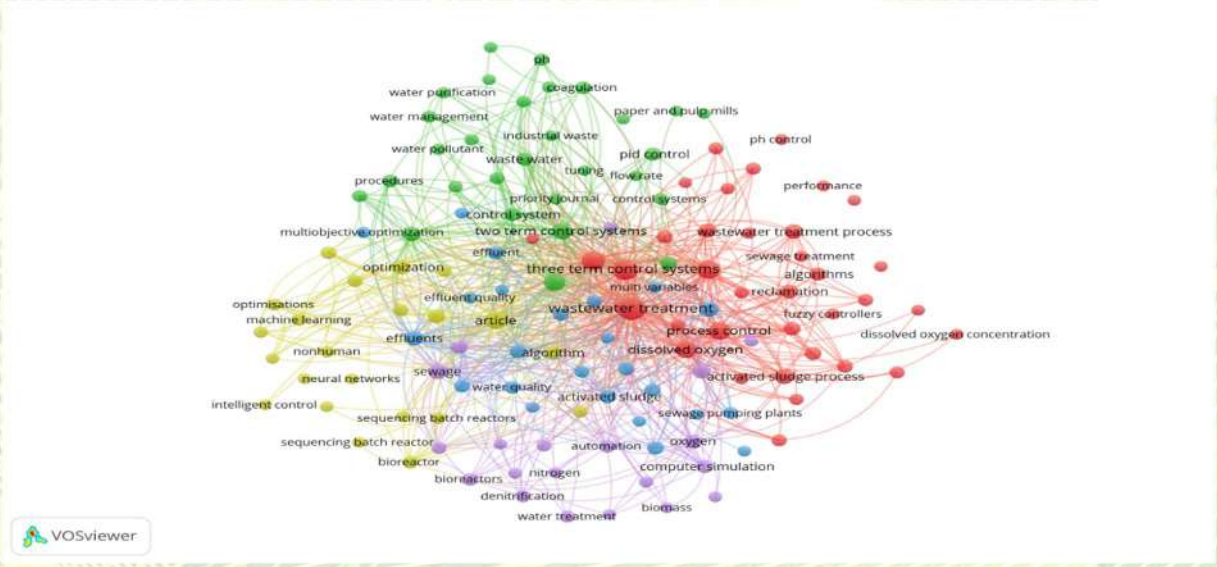


Figure 1. Keyword co-occurrence network of PID control in wastewater treatment

ISSN 3030-3907

As observed in the generated network visualization (Figure 1), the research landscape is divided into several distinct clusters:

- **Core Control Mechanisms (Red Cluster):** The central nodes are heavily focused on "wastewater treatment", "three term control systems" (PID), and "process control". This cluster demonstrates that traditional PID algorithms remain the foundational approach for managing fundamental parameters like "dissolved oxygen" and the "activated sludge process".
- **Advanced Optimization and AI (Yellow/Green Clusters):** A highly significant emerging trend is visible in the network featuring "machine learning", "neural networks", and "optimization". Crucially, this cluster is tightly linked to "energy efficiency" and "energy consumption". This indicates a clear paradigm shift: while traditional controllers maintain baseline stability, researchers are increasingly transitioning to AI-driven models to minimize energy expenditure.
- **Biological Processes (Blue Cluster):** This section of the map highlights the biochemical objectives of the control systems, containing keywords such as "nitrogen removal", "denitrification", and "biomass" management.

3.2. Global Scientific Production and Collaboration To further understand the global distribution of research on automated control in wastewater treatment, a country scientific production map was generated using the Mapchart.net package. As shown in Figure 2, the world map highlights the leading regions contributing to this specific field of study.



Figure 2. Global scientific production map of research on automated wastewater control

ISSN 3030-3907

The geographical distribution indicates that the most significant advancements in intelligent wastewater control systems are heavily concentrated in highly industrialized nations, which correlates with their stricter environmental regulations and higher energy costs.

3.3. Analysis of Highly Cited Documents Identifying the most frequently cited documents is crucial for understanding the foundational theories and breakthrough technologies in the automation of clarifier systems. Table 1 presents the top-cited and most relevant recent articles within the analyzed dataset, extracted via Scopus citation metrics.

Table 1.

Comparison of highly cited and recent automated control strategies in wastewater treatment.

Author & Year	Control Strategy	Target Process / Parameter	Key Finding / Efficiency Objective
Koumboulis et al. (2008)	Two-stage robust control	Activated sludge substrate concentration	Established a foundational mathematical framework for system stability.
Song et al. (2012)	Robust PID	Dissolved oxygen	Verified robust PID performance under dynamic wastewater conditions.
Piotrowski & Ujazdowski (2020)	Strategy design	Aeration systems	Evaluated optimization frameworks for biological aeration efficiency.
Revollar et al. (2021)	Multi-criteria control	Eco-efficiency in WWTPs	Evaluated the trade-offs between environmental compliance and operational costs.
Pisa et al. (2023)	Transfer Learning (AI)	Plant-wide control	Demonstrated the suitability of transferring machine learning models across different facilities.
Eshbobaev et al. (2024)	Fuzzy Logic - PID	Dissolved solids & hardness	Reduced settling time to 15s and decreased energy consumption by up to 2.3 kJ/m³.

ISSN 3030-3907

Chen et al. (2026)	CRS-Bayesian (AI)	Aeration & PAC dosing	Dynamically steered optimization to prioritize cost efficiency under stable conditions.
Hosseinnezhad et al. (2026)	Adaptive PID	Wastewater fluid transmission	Maintained long-term output stability within ±5% utilizing adaptive mechanisms.

3.4. Thematic Evolution and Trajectory of Control Strategies To further comprehend the technological progression within wastewater automation, a trend analysis of the literature reveals a distinct timeline of innovation. Initially, research heavily concentrated on establishing baseline mathematical stability using conventional Proportional-Integral-Derivative (PID) controllers. These early studies primarily targeted aeration systems and dissolved oxygen levels, as they represented the most immediate and visible parameters affecting effluent quality.

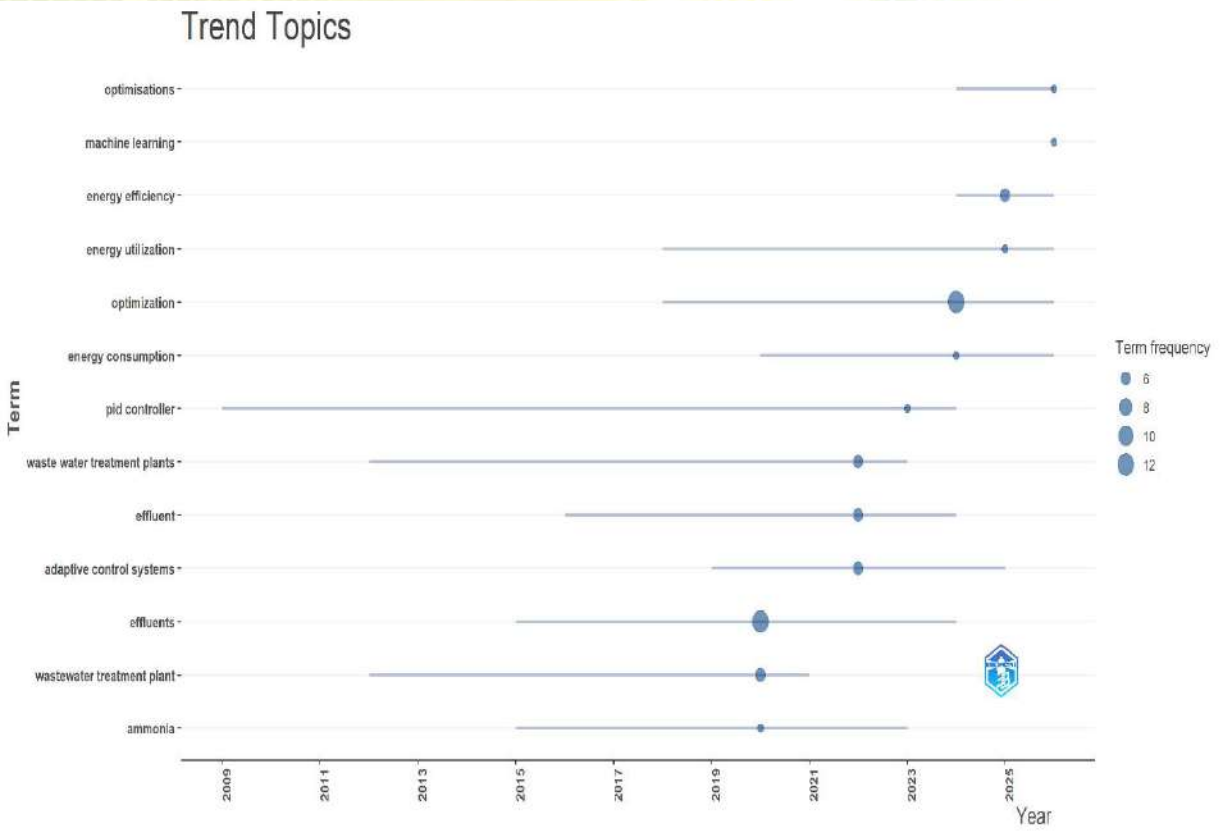


Figure 3. Trend topics evolution in automated wastewater control research.

However, the bibliometric data clearly indicates that within the last decade, the thematic focus has aggressively shifted towards "energy efficiency" and "optimization algorithms." The emergence of keywords such as "Fuzzy Logic," "Artificial Neural Networks," and "Adaptive Control" highlights a critical realization within the scientific community: while standard PID algorithms prevent

ISSN 3030-3907

system failure, they are fundamentally insufficient for minimizing dynamic energy expenditure under fluctuating biological loads.

3.5. Discussion of the Research Gap: The Clarifier Bottleneck Despite the rapid advancement in algorithmic control applied to aeration and chemical dosing, this bibliometric review uncovers a profound geographical and thematic gap regarding the physical separation processes. The visual network maps and highly cited documents show minimal concentration on the secondary clarifiers and the return activated sludge (RAS) pumping systems.

This oversight is highly significant for agro-industrial complexes (AIC). The concentration of activated sludge in sedimentation systems dictates the entire biological equilibrium of the treatment plant. When RAS pumps operate on static, unoptimized schedules or rely on delayed manual interventions, it not only leads to excessive electrical consumption but also causes severe destabilization of the microbiological purification process. Therefore, the bibliometric evidence strongly suggests that the next frontier in "Smart Water Management" is not merely upgrading aeration control, but rather digitizing the recirculation loops. Implementing hybrid intelligent systems capable of continuously monitoring and automatically adjusting the concentration of activated sludge in the sedimentation phase is the critical missing link for achieving holistic, plant-wide energy optimization.

4. CONCLUSION.

This comprehensive bibliometric review confirms that the automation of biological wastewater treatment within agro-industrial complexes (AIC) is undergoing a rapid and necessary evolution. The network analysis of highly cited Scopus literature reveals a definitive paradigm shift: while traditional PID controllers have historically provided foundational stability, the current research frontier is unequivocally dominated by the integration of Artificial Intelligence, Machine Learning, and adaptive optimization algorithms.

The primary driving force behind this technological shift is the critical need for **energy efficiency**. Biological treatment plants are exceptionally energy-intensive, and the bibliometric data clearly highlights that future automation strategies must prioritize the reduction of dynamic energy consumption. Specifically, this analysis uncovers a profound research gap regarding the secondary clarifier systems. While significant progress has been made globally in optimizing aeration tanks, there remains a vital need for empirical research focused specifically on digitizing the return activated sludge (RAS) pumping loops.

Developing hybrid intelligent control systems that can continuously monitor and dynamically regulate activated sludge concentration in the sedimentation phase

ISSN 3030-3907

represents the next crucial step for the industry. Addressing this specific bottleneck will enable true "Smart Water Management," ultimately ensuring strict environmental compliance while drastically minimizing the electrical and mechanical load of AIC pumping infrastructure.

REFERENCES

1. Pirimov O.J. Graph Models and Algorithm for Studying the Dynamics of a Linear Stationary System with Variable Delay - 2021 International Russian Automation Conference (RusAutoCon), 2021; pp. 431-436, doi: 10.1109/ /https://ieeexplore.ieee.org/document/9537328 (Scopus).
2. Pirimov O.J. The combination of artificial intelligence and solar energy: new approaches to powering electric vehicles in energy systems - International scientific journal science and innovation special issue: "modern problems and prospects of development of energy supply of digital technology facilities", march 1, 2024.
3. Pirimov O.J. Textbook for students of Higher Education Institution "Electronics and microprocessor technology" - TIQXMMI, Tashkent, 2020, 158 b
4. Koumboulis, F.N., Kouvakas, N.D., King, R.E., Stathaki, A. (2008). Two-stage robust control of substrate concentration for an activated sludge process. *ISA Transactions*, 47(3), 267–278.
5. Song, X.-L., Zhao, Y.-B., Song, Z.-Y., Liu, C.-Y. (2012). Dissolved oxygen control in wastewater treatment based on robust PID controller. *International Journal of Modelling Identification and Control*, 15(4), 297–303.
6. Piotrowski, R., Ujazdowski, T. (2020). Designing control strategies of aeration system in biological WWTP. *Energies*, 13(14), 3619.
7. Revollar, S., Meneses, M., Vilanova, R., Vega, P., Francisco, M. (2021). Eco-efficiency assessment of control actions in wastewater treatment plants. *Water (Switzerland)*, 13(5), 612.
8. Pisa, I., Morell, A., Vicario, J.L., Vilanova, R. (2023). Transfer Learning in wastewater treatment plants control: Measuring the transfer suitability. *Journal of Process Control*, 124, 36–53.
9. Eshbobaev, J., Norkobilov, A., Usmanov, K., Khamidov, B., Kodirov, O., Avezov, T. (2024). Control of Wastewater Treatment Processes Using a Fuzzy Logic Approach. *Engineering Proceedings*, 69, 39.
10. Chen, K., Yang, M., Gui, N., Tao, Y., Chen, Y., Wang, A., Liu, J. (2026). Integrated optimization of effluent quality, energy use, and chemical dosing in wastewater treatment using a cyclic residual-steered Bayesian framework. *Journal of Environmental Management*, 401, 128802.

ISSN 3030-3907

11. Hosseinnezhad, A., Sabri, H. (2026). Design and evaluation of a smart inline micro-hydro power plant for fluid transmission networks with adaptive control and self-cleaning capabilities. *Flow Measurement and Instrumentation*, 109, 103237.
12. Guo, C., Lv, M., Yang, Y., Yin, W., Yuan, Y. (2026). Automated multi-chemical dosing control based on machine learning for magnetic coagulation in aquaculture wastewater. *Journal of Environmental Management*, 404, 129388.

ISSN 3030-3907