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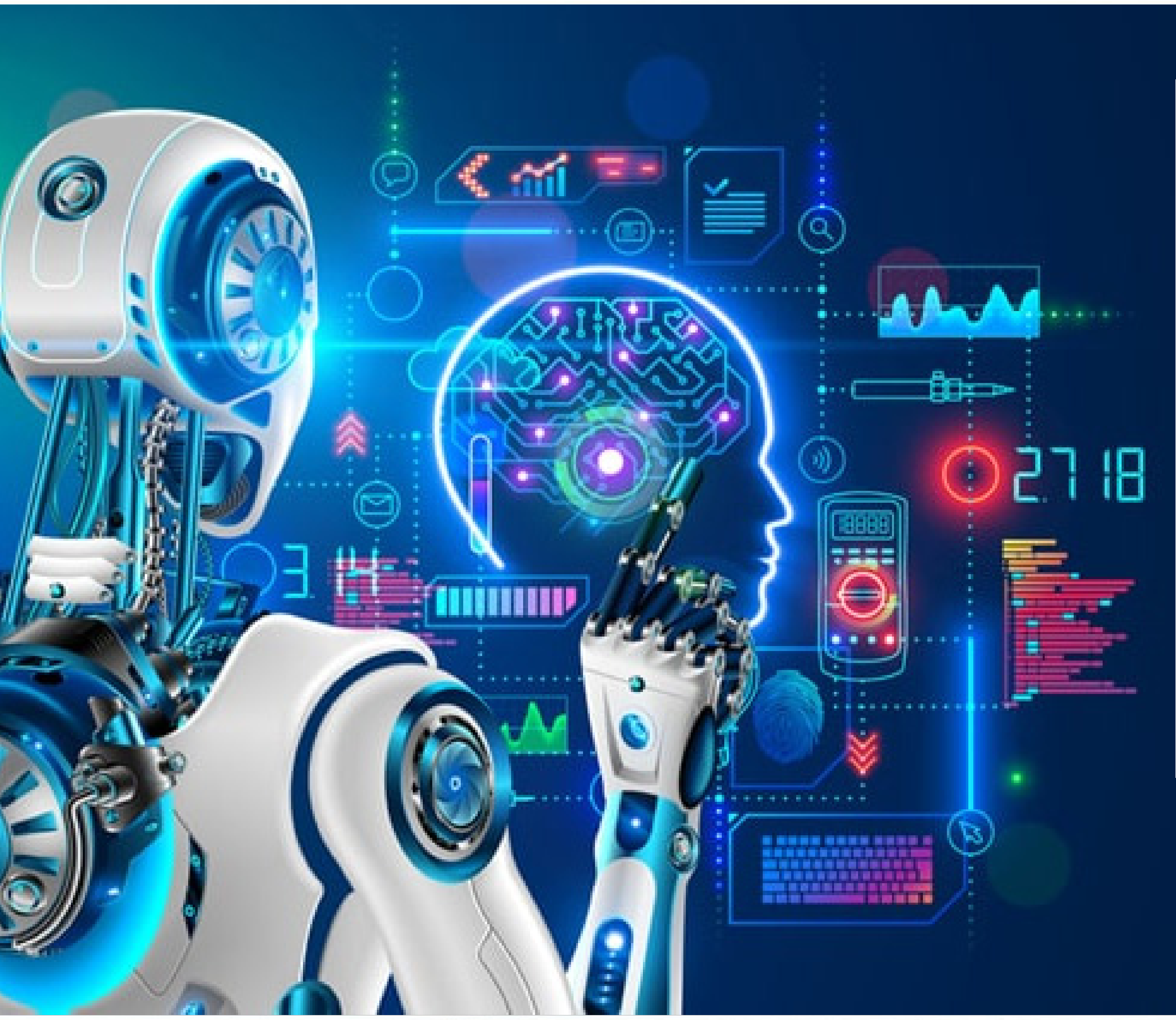

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CONTACTS

Phone: **+998 50 737 87 88**

Website: https://ist-journal.uz

Email: innovationist2025@gmail.com

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CONTENTS

INTEGRATION OF INTELLIGENT CONTROL IN DRYING SYSTEMS: PROCESS OPTIMIZATION THROUGH SENSORS, ARTIFICIAL INTELLIGENCE, AND MODULAR DRYING

Yangiboyeva Raxbaroy Mashrabboy qizi
Andijon davlat texnika instituti,
Mashinasozlik ishlab chiqarishini
avtomatlashtirish kafedrasi tayanch doktoranti,
Andijon, O‘zbekiston.
E-mail: yrakhbaroyaziza@gmail.com
ORCID: 0009-0004-8421-0706

Abstract: The article analyzes the integration of intelligent control systems—based on sensors, artificial intelligence, hybrid, and modular approaches—into industrial drying technologies. Traditional drying equipment typically operates according to predefined parameters such as temperature, airflow, and time, which often fail to deliver optimal results under varying conditions, raw material properties, and external factors. Therefore, the paper explores modern approaches including neural networks, neuro-fuzzy regulators, model-based control, data fusion, multimodal monitoring (hyperspectral imaging, computer vision), and cloud-based management systems.

The analysis shows that intelligent control-based drying systems can reduce energy consumption by up to 10–15%, shorten drying time, maintain consistent product moisture and quality, and significantly minimize operator errors. Moreover, modular and multi-agent architectures improve adaptability for various raw materials, while cloud monitoring enables remote control and large-scale data analysis. Integration with environmental monitoring raises drying technologies to a new level of energy efficiency and ecological safety.

Key words: Intelligent control systems, drying process optimization, artificial intelligence, sensor technologies, neural networks and fuzzy logic, hybrid control models, modular drying systems, cloud-based control, multimodal monitoring (data fusion), ecological monitoring and energy efficiency.

Annotatsiya: Maqolada sensorlar, sun'iy intellekt, gibrid va modulli yondashuvlarga asoslangan aqlli boshqaruv tizimlarining sanoat quritish texnologiyalariga integratsiyasi tahlil qilinadi. An'anaviy quritish uskunalari odatda harorat, havo oqimi va vaqt kabi oldindan belgilangan parametrlarga muvofiq ishlaydi, bu esa ko‘pincha turli sharoitlarda, xom ashyo xususiyatlari va tashqi omillar ostida optimal natijalarni bermaydi. Shuning uchun, maqolada neyron tarmoqlari, neyro-loyqa regulyatorlar, modelga asoslangan boshqaruv, ma'lumotlarni birlashtirish, multimodal monitoring (giperspektral tasvirlash, kompyuter ko‘rish) va bulutga asoslangan boshqaruv tizimlari kabi zamonaviy yondashuvlar o‘rganiladi.

Tahlil shuni ko‘rsatadiki, aqlli boshqaruvga asoslangan quritish tizimlari energiya sarfini 10-15% gacha kamaytirishi, quritish vaqtini qisqartirishi, mahsulot namligi va sifatini doimiy ravishda saqlab turishi va operator xatolarini sezilarli darajada kamaytirishi mumkin. Bundan tashqari, modulli va ko‘p agentli arxitekturalar turli xom ashyolar uchun moslashuvchanlikni yaxshilaydi, bulutli monitoring esa masofadan boshqarish va keng ko‘lamli ma'lumotlarni tahlil qilish imkonini beradi. Atrof-muhit monitoringi bilan integratsiya quritish texnologiyalarini energiya samaradorligi va ekologik xavfsizlikning yangi darajasiga ko‘taradi.

Kalit so‘zlar: Aqlli boshqaruv tizimlari, quritish jarayonini optimallashtirish, sun'iy intellekt, sensor texnologiyalari, neyron tarmoqlari va noaniq mantiq, gibrid boshqaruv modellari, modulli quritish tizimlari, bulutga asoslangan boshqaruv, multimodal monitoring (ma'lumotlarni birlashtirish), ekologik monitoring va energiya samaradorligi.

Аннотация: В статье анализируется интеграция интеллектуальных систем управления — на основе датчиков, искусственного интеллекта, гибридных и модульных подходов — в промышленные технологии сушки. Традиционное сушильное оборудование обычно работает в соответствии с предопределенными параметрами, такими как температура, поток воздуха и время, что часто не позволяет достичь оптимальных результатов в различных условиях, при различных свойствах сырья и внешних факторах. Поэтому в статье рассматриваются современные подходы, включая нейронные сети, нейро-нечеткие регуляторы, управление на основе моделей, слияние данных, многомодальный мониторинг (гиперспектральная визуализация, компьютерное зрение) и облачные системы управления. Анализ показывает, что интеллектуальные системы сушки на основе управления могут снизить энергопотребление на 10–15%, сократить время сушки, поддерживать постоянную влажность и качество продукта, а также значительно минимизировать ошибки оператора. Кроме того, модульные и многоагентные архитектуры повышают адаптивность к различным видам сырья, а облачный мониторинг обеспечивает дистанционное управление и крупномасштабный анализ данных. Интеграция с мониторингом окружающей среды выводит технологии сушки на новый уровень энергоэффективности и экологической безопасности.

Ключевые слова: интеллектуальные системы управления, оптимизация процесса сушки, искусственный интеллект, сенсорные технологии, нейронные сети и нечеткая логика, гибридные модели управления, модульные системы сушки, облачное управление, многомодальный мониторинг (слияние данных), экологический мониторинг и энергоэффективность.

INTRODUCTION

The drying process is one of the most essential and energy-intensive operations across many industrial sectors, including food processing, chemical production, pharmaceuticals, biomass, wood processing, and others. Traditional drying systems are typically configured based on static parameters such as temperature, airflow, and drying time; initial settings are predetermined and remain almost unchanged throughout the process. Although this approach is simple and convenient, it often leads to significant challenges when dealing with complex equipment designs, variable raw materials, and fluctuating external conditions — resulting in uneven drying, reduced product quality, excessive energy consumption, or instability in control performance.

Moreover, the complexity of drying processes increases due to the interdependence of factors such as moisture content, temperature, airflow, product type and properties, load volume, material and air movement, as well as heat and mass transfer mechanisms. Conventional automated control methods (e.g., static PID or temperature-based control, fixed airflow, predefined operating modes) are insufficient for ensuring optimal performance under such dynamic and uncertain conditions.

In recent years, the introduction of intelligent control systems into industrial dryers has led to substantial technological advancements. These systems enable real-time data acquisition from sensors, continuous monitoring of product and process parameters, adaptive control algorithms, artificial intelligence (AI) and machine learning techniques, neural and neuro-fuzzy regulators, multimodal monitoring (hyperspectral, optical, and other sensor technologies), and optimal/adaptive control strategies [1].

LITERTURE REVIEW

Intelligent control, unlike conventional automated control, relies on sensor data, real-time monitoring, model-based prediction, and adaptive algorithms (such as neural networks, neuro-fuzzy inference systems, and evolutionary/optimization algorithms). The drying process involves heat and mass transfer and often exhibits highly delicate, uncertain, or variable behavior: factors such as material composition, initial moisture content, air temperature/humidity, and airflow velocity are interdependent. Traditional control methods (e.g., static PID, PI, or fixed operating modes) may be insufficient for maintaining optimal performance under such complex conditions. Therefore, intelligent control systems are essential [2].

Intelligent control systems enable effective management of uncertainty and variability in drying processes. Parameters such as product type, moisture level, air conditions, and load volume are monitored in real time, and the process is automatically adjusted accordingly. As a result, energy consumption decreases, and efficiency improves by reducing excessive heating and airflow.

These systems also enhance product quality — ensuring uniform drying while preserving color, texture, and aroma in heat-sensitive materials. Process stability and reliability increase, operator errors are reduced, and labor costs decline.

Moreover, intelligent dryers are flexible and adaptable to various raw material types, operating efficiently across a wide range of conditions. Data collected during the drying process is stored and later used for process analysis and optimization, enabling continuous technological improvement. This approach elevates automated drying to a new stage — “smart, adaptive, data-driven, and optimized drying.”

In one study, a control system integrating sensors, artificial intelligence, and fuzzy logic algorithms was implemented in a real drying unit, resulting in a 12–15% reduction in drying time, a 10–12% decrease in energy consumption, and improved moisture uniformity [3]. Another study showed that applying an artificial neural network–based NARMA-L2 controller to a conveyor dryer during fruit drying reduced stabilization time by 57% and errors by 74% compared to classical PID control — leading to more consistent product quality and greater energy savings [4].

Thus, industrial drying technologies are shifting from simple, rigid operating modes to adaptive, intelligent systems driven by real-time data. This transition is rapidly expanding both technically and practically. Modern sensor technologies, machine learning, neuro-regulators, fuzzy logic, model-based control, and optimization algorithms make drying processes significantly more efficient, higher in quality, and environmentally friendlier.

In the future, it is expected that drying systems will increasingly integrate IoT, 5G, cloud technologies, high-precision sensors, and real-time data analytics platforms. Such “factory-to-cloud” control architectures will enable global analysis, remote monitoring, and comprehensive supervision of drying operations [5].

RESEARCH METHODOLOGY

In the study, real-time data from sensors installed in the drying system (moisture, temperature, and airflow) were collected. These data were processed using artificial intelligence and fuzzy logic algorithms to determine the optimal drying regimes. The results of the intelligent control were compared with those of conventional control, and differences in energy consumption, drying time, and product quality were evaluated. Finally, the developed algorithm was tested on a modular dryer, and its effectiveness was confirmed.

ANALYSIS AND RESULTS

Current state and methods of intelligent control systems. At present, intelligent systems based on artificial intelligence and neural networks are widely used in controlling drying processes.

In one study, a NARMA-L2 type neural network controller operating in real time was applied to a conveyor dryer designed for fruit drying. With the help of this intelligent control system, the relative humidity inside the drying chamber is continuously monitored, and the process is controlled accurately and stably [4]. According to the research results, compared to the classical PID controller, the stabilization time of the process was reduced by 57%, and the overshoot was reduced by 74%. This significantly decreased energy consumption, increased the efficiency of the drying process, and made it possible to maintain product quality at a stable level.

Combining control methods — hybrid control systems. Hybrid control systems are among the most promising directions in modern drying processes, especially under complex and variable conditions. For example, in a study on sliced tobacco, an intelligent control system is applied to an industrial rotary dryer: in this case, the moisture content at the dryer outlet is selected as the main controlled parameter, while the temperature of the drying air serves as the manipulating variable [2]. The system operates without operator intervention, based on continuous real-time monitoring and readjustment, maintaining moisture at an optimal level, preventing overdrying, and significantly improving product uniformity and quality. At the same time, a reduction in waste and energy consumption has been observed, which confirms the practical effectiveness of hybrid control.

In another modern work [6], a hybrid approach consisting of a physics-based model and a data-driven component is proposed for pneumatic drying processes. The authors use a conventional mechanical/thermal model to describe the main physical laws of the process and employ artificial intelligence methods to learn the residual dynamics in order to capture remaining uncertainties and nonlinearities. As a result, very high accuracy is achieved for outlet moisture and temperature (mean absolute error of about 0.016% moisture and about 0.015 °C temperature), along with a stable model suitable for control. Such a hybrid structure increases robustness against disturbances caused by external factors, ensures system stability, and is developed in a form that can be directly connected to model-based control (MPC and others).

Data fusion and multimodal monitoring. In recent years, in order to control drying processes more precisely, data fusion of sensor signals—i.e., jointly analyzing data obtained from different sources such as temperature, air flow, time, and images—has been widely used. In one study on apple drying, not only process parameters but also images of the dried pieces were used [7]. This approach has been shown to be much more effective than traditional parameter-only methods in accurately predicting moisture content and controlling the drying process.

Furthermore, in [Zhe Wang, Min Zhang, Arun S. Mujumdar, Jiacong Lin, Dongxing Yu, AI technology in smart drying of foods: A critical review of research and applications, Innovative Food Science & Emerging Technologies, Volume 103, 2025], artificial intelligence, IoT sensors, computer vision, hyperspectral imaging, and other advanced technologies are highlighted as key directions for online monitoring, quality control, energy saving, and process optimization in drying operations.

Through such integrated systems, every stage of the drying process can be monitored with high accuracy, enabling the preservation of product quality and the improvement of energy efficiency.

Modular and optimized drying processes + optimization algorithms. In one study, it is recommended to design and optimize the drying process in a modular manner, that is, to create systems in which several drying methods (convection, vacuum, pneumatic, and others) are used sequentially [8]. This method achieved up to a 12% reduction in energy consumption compared to a single-stage system.

This approach is particularly beneficial for enterprises working with various types of raw materials (grain, biomass, fruit, polymers, etc.), as maximum efficiency can be achieved by configuring the modules in the required sequence and with appropriate parameters.

Advantages and disadvantages of the intellectualization of drying processes. The advantages of intelligent drying systems and the aspects that must be considered when implementing them manifest themselves in several directions. First of all, in such systems, processes are under continuous control, and many parameters such as moisture, temperature, and air flow are measured and automatically regulated in real time. This ensures the stability of product quality and reduces production errors. The combination of artificial intelligence, sensor networks, multimodal monitoring, and modular design enhances energy efficiency and resource savings. Studies show that such systems significantly reduce energy consumption and drying time [3].

In addition, intelligent control systems are flexible with respect to different types of raw materials and drying methods, and they can be tuned according to the required quality specifications. Automated control reduces human intervention, minimizes operator errors, and continuously stores monitoring results for further analysis and optimization.

At the same time, it is necessary to pay attention to certain risks and limitations when implementing such systems. Reliable operation of artificial intelligence and hybrid models requires large-scale real data, dense sensor networks, and monitoring infrastructure. This leads to high initial investment and technical costs. In some cases, due to the complexity of the control algorithms, incorrect parameter tuning may negatively affect product quality. Moreover, the accuracy and reliability of sensor and data transmission systems are of critical importance—even small errors can disrupt control. For different products and drying methods, separate models, testing procedures, and optimization are required, since there is no universal solution.

New approaches to the implementation of intelligent control systems in drying technologies. Today, intelligent control systems remain an area that is not yet fully explored and is still in the development stage. Scientific research shows that deeper integration of artificial intelligence into drying technologies, automation of data analysis, and the creation of self-learning systems have not yet been fully implemented. Below are some promising, but not yet widely applied, new approaches:

Self-learning drying systems. Traditional physical models that describe drying processes (heat–mass transfer, evaporation kinetics, etc.) are often insufficient for real-time control and optimization [9]. At the same time, drying processes depend on numerous variable factors: moisture content, product type, air conditions, load volume, raw material properties, and others. These factors make accurate prediction and optimization difficult [10]. Therefore, data-driven, adaptive control—i.e., systems that "learn" from their own experience and can automatically select optimal parameters in subsequent cycles—can significantly improve drying efficiency, product quality, and energy efficiency [9].

Cloud-based control. All drying processes are connected to a single central platform via the Internet. This allows enterprises to remotely control several drying lines simultaneously and analyze their data. Cloud-based control systems make it possible to monitor the drying process remotely—an operator can manage all parameters via the Internet without being physically present. This is a convenient solution for large enterprises and branch networks, as multiple lines are controlled from a single center.

The system can store and analyze data, keeping process efficiency and product quality under constant supervision. Through automation and algorithmic control, energy and labor costs are reduced. As a result, product quality remains stable, parameters are standardized, and quality control becomes more reliable [11, 12, 13].

Digital twin technology. A virtual copy of the real dryer is created. Through this digital twin, the process is simulated, results are predicted in advance, and optimal control regimes are tested without affecting actual production [14].

AI-assisted energy consumption optimization. Artificial intelligence continuously analyzes energy usage and maintains heat transfer in the most efficient regime. This not only reduces electricity consumption but also enables the reuse of waste heat.

Drying processes are among the most energy-intensive operations in industry. However, traditional control parameters (fixed temperature, air flow, time) are not always optimal, given the great variety in product type, initial moisture content, and ambient conditions.

It is noted in the research that machine learning algorithms are an effective tool for reducing energy consumption in drying processes, using different energy sources, and increasing energy efficiency [10].

Vision-based quality control. This refers to continuously monitoring the surface condition, color, structure, moisture state, and other visual or spectral properties of the raw material or product being dried, using cameras or hyperspectral imaging. If the system is combined with artificial intelligence (such as machine learning or neural networks), it automatically analyzes the information obtained from the images and decides whether to stop or continue the drying process at the appropriate stage.

This method has advantages over traditional moisture measurement techniques (gravimetric, chemical analysis, etc.): it is fast, non-destructive, and allows real-time monitoring of the entire batch, not just individual samples.

It is particularly effective when drying fruits and vegetables, grains, nuts, biomass, and other natural raw materials with uneven moisture distribution, heterogeneity, and delicate structure [15].

Multi-agent control. In multi-agent control, several intelligent drying modules are interconnected and exchange information with each other. Each module analyzes its own state and contributes to improving the efficiency of the overall system.

Although there are currently few publications specifically on multi-agent control in drying, this method is widely used in industrial control, energy systems, and complex process management, which suggests that its application to drying systems is likely to be beneficial.

The article “A Survey of Multi-Agent Systems for Smartgrids” shows that multi-agent control is widely used in energy systems to manage complex and variable conditions [16].

In [17], examples of integrating multi-agent control into industrial control networks are discussed. They demonstrate that legacy control systems can be extended with an agent-based layer, turning them into flexible systems with multi-module control.

Integration with environmental monitoring. In the future, drying systems will monitor not only product quality but also their impact on the environment. For example, real-time monitoring will be established for waste heat, carbon dioxide emissions, and air pollution levels. Drying processes are often associated with high energy consumption, heat sources, and emissions to the atmosphere (gases, steam, pollutants). If these are not controlled, they can cause environmental harm, air pollution, and energy waste.

In the current context of environmental and climate change, there are strict requirements regarding the carbon footprint, emissions, and efficient use of resources in industrial processes. Drying processes also need to be analyzed within this framework [18].

Integration with environmental monitoring—i.e., adding sensors and monitoring systems that measure emissions, waste heat, air quality, and exhaust gases to the dryer—ensures real-time monitoring and control of these factors.

Thus, the drying system should be reconsidered not merely as a tool to reduce product moisture content but as a process that combines “efficient use of resources + no harm to the environment.”

Although these approaches have not yet been fully implemented in practice, they are expected to determine the direction of development for industrial dryers in the coming years. Their main goal is to transform the process into a more intelligent, environmentally safe, energy-efficient, and human-independent control system.

CONCLUSION AND RECOMMENDATIONS

The analyses carried out show that drying systems based on traditional static regimes can no longer fully meet current industrial requirements—high quality, energy efficiency, environmental safety, and flexibility. Since the drying process is inherently multi-variable, highly uncertain, and nonlinear, its effective control requires data-driven intelligent control systems that are rich in sensors and equipped with real-time monitoring.

Regulators built on neural networks, neuro-fuzzy algorithms, and hybrid (physical model + data-driven) approaches have been shown in the scientific literature to shorten the stabilization time of the drying process, reduce overshoot and errors, and maintain outlet moisture more accurately. Through data fusion and multimodal monitoring, it becomes possible to assess not only process parameters but also the actual state of the product (color, structure, moisture distribution), which raises quality control to a new level.

Solutions based on cloud control and IoT technologies create wide opportunities for remote monitoring, centralized control of multiple drying lines, maintaining a historical database, and further optimization. Multi-agent architectures and modular drying lines, in turn, make it possible to expand the system step by step, adapt it to different raw materials and regimes, and increase fault tolerance.

Integration with environmental monitoring—real-time control of emissions, waste heat, and energy balance—allows intelligent drying systems to be aligned with “green technology” principles, reducing the carbon footprint and enabling efficient use of resources. Overall, intelligent drying systems that combine sensors, artificial intelligence, hybrid models, cloud control, and environmental monitoring represent the main direction for future industrial drying technologies, and their in-depth study and practical implementation constitute an urgent scientific and applied task.

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