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THE ROLE OF METROLOGY IN ENSURING FOOD SECURITY: CONTROL METHODS BASED ON DIGITAL TECHNOLOGIES

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Annotation: In the context of global challenges—climate change, population growth, and resource constraints—food security has become a key priority of state policy. Metrology, as the science of measurement, plays a crucial role in ensuring the quality and safety of food products. Modern digital technologies—such as sensors, artificial intelligence, IoT, and traceability systems —enhance the accuracy, reliability, and efficiency of food quality control at all stages of the agri-food supply chain. This article explores modern approaches to metrological support in the agro-industrial sector, emphasizing digital transformation and international standards.
Keywords: metrology, food security, digital technologies, quality control, IoT, ISO standards, agro-industrial complex, traceability.
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In the 21st century, ensuring food security has become especially relevant due to global challenges such as climate change, population growth, urbanization, and limited natural resources. The quality and safety of food products directly affect public health, sustainable development, and the economic stability of nations. Under these circumstances, effective control over the production, transportation, storage, and distribution of food products is gaining increasing importance.

Metrology, as the science of measurements and the assurance of their accuracy, plays a key role in building trust in food products. Reliable measurements of mass, volume, composition, calorific value, content of harmful substances, and other parameters serve as the foundation for objectively assessing product quality and ensuring compliance with regulatory requirements. With the advancement of digital technologies, methods of metrological control are also undergoing significant changes. Smart sensors, the Internet of Things (IoT), automated laboratories, cloud databases, artificial intelligence technologies, and blockchain offer new opportunities for comprehensive and rapid control at all stages of the agri-food supply chain. These tools enhance the accuracy, traceability, and transparency of processes related to the production and delivery of food.

This article is devoted to analyzing the role of metrology in ensuring food security, with a focus on the implementation of digital solutions in quality control systems. It also examines international standards and successful practices applied in various countries, including Uzbekistan.

In the modern context of food security, metrology plays a crucial role as an integral part of both national and international systems for controlling the quality of food products. Without precise and reliable measurements, it is impossible to ensure compliance with sanitary, hygienic, and technological standards, as well as the requirements related to product traceability at all stages of the supply chain—from production to consumption.

One of the most important areas of applying metrology in the food sector is the control of parameters that impact human health. These include the content of harmful impurities (nitrates, heavy metals, pesticides), compliance with physical and chemical indicators (temperature,

humidity, acidity, mass fraction of fat, protein, and sugar) with established norms, as well as the accuracy of product packaging and labeling.

Metrological tools and methods ensure the following:

– Accurate determination of the composition and quality of raw materials and finished products;
– Compliance with technological processes during production;
– Assessment of shelf life and transportation conditions;
– Verification of product compliance with established standards and regulations;
– Protection of consumer rights from falsification and misleading information on packaging.

The reliability of such measurements is ensured by a comprehensive system of measures. In particular, this includes regular verification and calibration of measuring instruments, certification of laboratory equipment, adherence to internationally recognized testing methods, and the availability of accredited laboratories competent in conducting food analysis.

All these components are part of a unified national metrological system, which must operate in close coordination with international organizations such as the OIML and Codex Alimentarius. Furthermore, metrology contributes to building trust in the market—both among consumers and between producers, regulatory authorities, and trading partners. In the context of globalization and the expansion of agricultural and food exports, it is especially important that measurement results are recognized internationally. This requires the harmonization of standards, the unification of analytical methods, and mutual recognition of calibration and testing results.

Thus, metrology is not merely an auxiliary tool in the field of food security but a strategically important component that ensures the accuracy, objectivity, and scientific validity of all decisions made in this domain. Through metrological assurance, a high level of trust in products is achieved—regarding their safety and compliance with regulations—which ultimately affects public health and the sustainability of food systems. The modern development of digital technologies is having a profound impact on all sectors of the economy, and the field of metrological control over the quality and safety of food products is no exception. Digitalization opens up new opportunities for more accurate, timely, and transparent control and contributes to enhancing the efficiency of all processes—from production to consumption.

One of the key areas of digital transformation is the implementation of automated measurement systems capable of real-time monitoring of product parameters at various stages of the technological chain. For example, modern sensors integrated into production lines allow continuous control of temperature, humidity, acidity, sugar content, salt, and other indicators without interrupting the process. Digital laboratories and measuring instruments connected to network platforms enable remote monitoring and data analysis, which is especially important for large-scale production or product export. The use of cloud-based solutions ensures secure storage, analysis, and access to product data, as well as streamlines auditing, certification, and export-import procedures. Blockchain technologies are becoming increasingly important, as they ensure the immutability and traceability of metrological data. With the help of a distributed ledger, every measurement taken during production, packaging, and logistics can be recorded. This increases trust among all participants in the supply chain and minimizes the risk of data falsification.

Moreover, digital platforms for exchanging metrological information among enterprises, laboratories, and government bodies are actively developing. These systems help reduce paper-based documentation, accelerate certificate authentication, and simplify accreditation and calibration procedures.

An important element of digitalization is the introduction of electronic labels and QR codes on food packaging, through which consumers can access real-time information not only about the product's composition, expiration date, and manufacturer, but also about the results of metrological testing. This enhances transparency and strengthens trust in the product. Thus, digitalization of metrological control in the food industry is not just a trend but a strategic direction, ensuring a higher level of quality, safety, and sustainability of food systems. At the same time, it is essential that the implementation of digital technologies is supported by appropriate legal and regulatory frameworks, as well as the development of competencies among specialists working in this field.

The reliability and accuracy of measurements in the food industry are directly linked to the effectiveness of the regulatory and legal framework governing metrological activities. Legislative and regulatory mechanisms in this area form the foundation for the uniformity of measurements, mutual recognition of test results, and high-level consumer rights protection. In many countries, including Uzbekistan, metrological support is an integral part of the food security system. National laws on technical regulation and metrology include requirements for measuring instruments, their verification, calibration, and operation rules. These standards apply at all stages — from incoming raw material inspection to the release of finished products and their sale on the market.

Metrological aspects are also actively regulated by international organizations such as the OIML (International Organization of Legal Metrology), Codex Alimentarius, and ISO. These bodies develop model laws, guidelines, and international standards that help harmonize requirements across countries. This is especially important in the context of globalized food markets and cross-border trade. In recent years, there has been a significant update of legislation in response to digital technologies. The introduction of electronic measuring instruments requires regulatory definitions of terms such as “electronic verification,” “digital traceability,” and “remote calibration.” In Uzbekistan, the development of regulatory documents aimed at integrating digital solutions into the metrological practices of the food sector has already begun.

One of the key goals of legislation is the protection of consumer interests. Consumer protection laws include provisions requiring manufacturers and sellers to ensure the accuracy of information regarding product composition, nutritional value, and potential health risks. Violations in this area are treated as administrative offenses and may result in fines or product bans.

Particular attention is given to the accreditation and oversight of metrological laboratories. Only institutions accredited according to international standards have the right to conduct measurements whose results are recognized within the food safety assurance system. National accreditation bodies, such as TJTS, play an important role in this process. Thus, the legal framework for metrological control in the food industry represents a multi-layered system that combines national and international regulation, ensures measurement quality, and forms the basis for a transparent and safe food market. Updating these norms in line with digital advancements is a vital step toward strengthening the country's food security resilience.

Modern trends in the food industry require high-precision, automated, and adaptive systems for quality control of food products. Digital metrology is becoming a central element of these transformations, offering innovative tools for measurement, analysis, and traceability at all stages of the food supply chain — from field to shelf. One of the key directions is the use of smart sensors and the Internet of Things (IoT), which enable continuous monitoring of environmental parameters, storage conditions, and transportation of products. For example, temperature, humidity, and gas sensors can be embedded into packaging or equipment and

transmit data in real-time to centralized systems. Digital calibration and remote verification of measuring instruments are also becoming important trends. Instead of requiring the physical intervention of specialists, automatic instrument verification can now be carried out using secure digital channels and cloud technologies. This is particularly relevant for large-scale processing enterprises with a wide array of measuring devices.

Furthermore, the use of artificial intelligence (AI) and machine learning in metrology is moving to the forefront. Data analysis algorithms make it possible to identify hidden relationships between raw material parameters and the quality of finished products, predict deviations, and optimize production processes.Below is a comparative table of the most common digital solutions in food industry metrology and their key benefits:

Comparative Table of Digital Solutions in Food Metrology

№	Digital Solution	Description	Main Advantages
1	Smart sensors (IoT)	Sensors for monitoring temperature, humidity, gas, etc.	Continuous control, automatic alerts
2	Cloud-based measurement platforms	Online data storage and analysis of instrument readings	Centralized access, transparency, availability
3	Remote calibration and verification	Checking accuracy without physical access	Cost and time savings, less human intervention
4	AI/ML for metrological data analysis	Processing large datasets for prediction and optimization	Pattern detection, predictive maintenance, quality improvement

The implementation of such solutions requires the training of specialists, adaptation of regulatory documents, and technical modernization of enterprises. However, the prospects for their use are clear: increased measurement accuracy, risk reduction, improved traceability, and, as a result, enhanced consumer trust.

In the coming years, we can expect the further spread of digital twins for food production facilities, integration of metrological systems into big data platforms, and the development of international digital standards. All of this makes digital metrology an integral part of a sustainable and safe food system of the future.

The current challenges in food security demand a comprehensive approach based on the integration of digital technologies and metrological control. The conducted analysis shows that traditional methods of assessing food quality no longer meet the requirements of the digital economy and the rapidly evolving agri-food sector. Therefore, the implementation of digital solutions into metrological practice becomes a key factor in increasing measurement accuracy, process transparency, and consumer trust.

Based on the results of the study, the following key conclusions and practical recommendations can be made:

1. Integration of digital technologies into metrological control — the use of IoT sensors, artificial intelligence systems, and cloud platforms enables continuous and accurate monitoring of product quality.
2. Updating the regulatory framework — it is necessary to adapt existing standards and technical regulations to modern digital realities and trends.
3. Training and upskilling — special attention should be given to educating specialists who can effectively use digital measuring tools and perform analytical assessments.

4. Strengthening international cooperation — harmonizing national requirements with international standards (ISO, Codex Alimentarius, OIML) will enhance export potential and improve internal control systems.
5. Creation of innovative laboratories and technoparks — scientific and research initiatives aimed at developing new digital solutions in the field of metrology and food safety should be supported.

In conclusion, the transition to digital metrology in the food safety assurance system is a strategically important step. It not only contributes to improving product quality and safety, but also ensures the sustainable development of the sector, public health protection, and consumer confidence. The implementation of the proposed measures will serve as the foundation for building a modern, technologically advanced, and human-centered quality control system.

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