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Digitalization as a Factor in Improving the Quality of Greenhouse Products: From Automation to Predictive Analytics

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Abstract: The article examines the role of digital technologies in ensuring high-quality production in greenhouse farming. The use of information and communication solutions, including sensor networks, automated control systems, and computer vision technologies, enables the effective optimization of microclimate parameters, irrigation, plant nutrition, and pest control. This leads to increased yields and improved product quality. The digital transformation of greenhouse production serves as a key factor in enhancing the competitiveness of the agricultural sector. The introduction of artificial intelligence and machine learning algorithms opens up new opportunities for forecasting, sustainable development, and the improvement of production processes.

Key words: digitalization, greenhouse farming, automation, microclimate, precision agriculture, predictive analytics, yield, product quality.

In the modern agro-industrial complex, where greenhouse production involves a high concentration of resources and the use of advanced technologies, the search for effective solutions to increase productivity and improve crop quality continues relentlessly.

A particularly important role in this process is played by **digitalization**, i.e., the integration of information and communication technologies (ICT) into all aspects of greenhouse management and operation. The use of digital management tools enables comprehensive optimization of the production cycle — from the planning stage to the distribution of the final product. This contributes to improved crop quality, increased yields, and higher economic efficiency of agricultural enterprises.This article examines in detail the impact of digitalization on the improvement of greenhouse production quality, as well as analyzes the key stages of this process — from basic automation of operations to the implementation of advanced forecasting systems.

1. Automated Microclimate Control as the Basis of Quality Production

The creation of an optimal microclimate is a decisive factor in obtaining high-quality greenhouse products. Traditional regulation methods, based on manual control and periodic parameter adjustments, cannot ensure the necessary precision and responsiveness required for creating favorable growth conditions.

Digitalization helps to overcome these limitations through the introduction of automated systems, which include:

- **Sensor networks.** Sensors placed throughout the greenhouse continuously measure air and soil temperature, humidity levels, light intensity, CO_2 and oxygen concentration, and other critical parameters. Modern sensor devices are highly accurate, reliable, and capable of transmitting real-time data.
- **Automated control systems.** A central control platform processes incoming sensor data and, using embedded algorithms, automatically regulates heating, ventilation, lighting, shading, irrigation, and other engineering systems. This ensures stable microclimate conditions with minimal deviations, reduces plant stress, and improves crop quality.

Forecasting system. By using accumulated historical data, weather forecasts, and current greenhouse conditions, the system can predict changes in microclimatic parameters hours or even days in advance. This proactive approach allows early adjustments to equipment operation, minimizing the risks of adverse weather conditions.

Data visualization system. Modern digital platforms provide user-friendly tools for displaying data, enabling operators to monitor greenhouse conditions in real time and respond promptly to any changes. This greatly simplifies monitoring and process control, particularly in large-scale greenhouse complexes.

2. Precision Irrigation as the Key to High Yields

Efficient irrigation is one of the most critical factors for ensuring quality greenhouse production. Disruption of the water regime — whether over-irrigation or insufficient watering — can negatively affect crop volume, taste characteristics, and even trigger plant diseases. The use of digital technologies enables the development of optimal irrigation strategies:

- **Automated drip irrigation.** Modern drip irrigation systems with automated control deliver precise amounts of water and nutrients directly to the plant root zone. This minimizes resource losses and eliminates the risks of soil over-saturation or drying out.
- **Soil moisture sensors.** Integrating moisture sensors into irrigation systems allows real-time monitoring of substrate conditions and rapid adjustments to water supply according to plant needs. This approach ensures rational use of water resources and reduces the risk of diseases caused by excessive humidity.
- **Intelligent management systems.** Cutting-edge solutions rely on a combination of factors — weather data, soil moisture, nutrient concentration, and plant growth stages. These systems generate optimal irrigation schedules, ensuring maximum efficiency of water and fertilizer use while improving the overall quality of production.

3. Optimization of Plant Nutrition: A Balanced and Precise Approach

Proper plant nutrition serves as the foundation for achieving stable and abundant yields, as well as high-quality produce. Digital technologies allow for significantly improved precision and efficiency in managing nutrition:

- Fertigation systems with drip irrigation. Automated installations ensure accurate delivery of nutrients to the root system simultaneously with water supply, maintaining balanced nutrition throughout all stages of plant growth and development.
- Assessment of soil and nutrient solution composition. Modern analytical methods allow timely identification of nutrient deficiencies or surpluses in soil and irrigation solutions. This enables prompt adjustments in the fertilization program, ensuring complete and harmonious plant development.

Plant Condition Monitoring

The use of computer vision and image processing technologies makes it possible to comprehensively assess crop conditions, detecting the first signs of nutrient deficiencies or diseases. This approach enables timely intervention and prevents yield quality reduction.

Formula for Nutrient Balance

Nutrient Uptake Efficiency (NUE) can be expressed as:

$$NUE = (N_{absorbed} / N_{supplied}) \times 100\%$$

Where:

$N_{absorbed}$ – the amount of nutrients absorbed by plants (mg/L),

$N_{supplied}$ – the total nutrients provided through fertigation (mg/L).

4. Plant Protection: Preventive Measures and Timely Actions

Digital technologies significantly increase the effectiveness of plant protection against diseases and pests:

- Early detection systems. The application of computer vision algorithms and image analysis allows the identification of initial signs of diseases or pest activity at an early stage, when effective containment measures can still be applied.
- Automated treatment systems. Intelligent spraying installations ensure precise dosing of plant protection products, which simultaneously improves treatment effectiveness and reduces the potential negative impact on the environment.
- Prediction of pest and disease activity. Analysis of climate conditions, humidity, temperature, and other parameters, combined with historical data on disease outbreaks and pest infestations, allows forecasting of their occurrence and taking preventive measures in advance.

5. Lighting: Stimulation of Photosynthesis

The light regime is one of the key factors influencing photosynthesis and the overall development of plants. The introduction of digital technologies makes it possible to achieve optimal lighting conditions:

- **Light regulation based on data.** Automated systems adjust the intensity and duration of the photoperiod depending on the plant growth stage, time of day, and weather conditions.
- **Control of the spectral composition of light.** The use of LED lamps with adjustable spectra allows for the selection of the most suitable light conditions for different crops, stimulating photosynthetic processes and improving crop quality.

6. Predictive Analytics: Anticipation and Process Improvement

The integration of predictive analytics is considered a new stage in the digital transformation of greenhouse production. Processing large datasets collected from sensors and intelligent systems increases management efficiency and minimizes risks:

- **Yield forecasting.** Based on historical data analysis, microclimatic conditions, plant nutrition specifics, and other factors, the system can accurately estimate expected yields at different stages of growth.
- **Identification of potential risks.** Data analysis enables early detection of threats such as disease outbreaks, nutrient deficiencies, or inefficient water use at the initial stages of their occurrence.

- **Optimization of technological processes.** Predictive analytics helps improve irrigation, nutrition, and plant protection systems, positively affecting yield and product quality.

7. Data Integration and Digital Platforms

For the effective use of digital technologies in greenhouses, it is essential to integrate information coming from different sources. This is achieved through digital platforms that provide the following opportunities:

- Unified Data Processing Center: All information collected from sensors and other sources is stored and processed in a single location.
- Integration of Different Systems: The digital platform combines various management systems, such as climate control, irrigation, fertilization, and plant protection.
- Instant Access to Information: Operators have immediate access to real-time data through a user-friendly interface.

Digital technologies are gaining increasing importance in improving the quality of greenhouse production. The implementation of modern solutions allows optimization of all production stages, which leads to higher yields, improved quality, reduced costs, and overall increased productivity.

The transition to digital management methods is not just modernization but a critical step toward creating a modern and competitive greenhouse complex. The development of technologies such as artificial intelligence (AI) and machine learning (ML) will enable the creation of smarter and more flexible management systems, ensuring an even higher level of product quality and production efficiency.

Mathematical Formulas in the Context of Digital Greenhouses

1. Photosynthetic Efficiency

$Ep = (P\_out / P\_in) \times 100\%$

where: P_out = actual photosynthetic output ($g/m^2/day$), P_in = theoretical maximum output.

2. Water Use Efficiency (WUE):

$WUE = Y / ET$

where: Y = yield (kg/m^2), ET = evapotranspiration (L/m^2).

3. Digital Climate Control Index (simplified model):

$DCCI = \alpha T + \beta H + \gamma CO_2$

where: T = temperature factor, H = humidity factor, CO_2 = concentration factor, α, β, γ = weight coefficients determined by AI algorithms.

These formulas demonstrate how digitalization makes it possible to measure, monitor, and optimize key parameters in greenhouse operations, creating a foundation for smart agriculture.

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