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Opinion Article

Virtual Replicas for Real-Time Optimization of Food Manufacturing Systems

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DESCRIPTION

Digital Twin (DT) technology is becoming an important component of intelligent food processing. A digital twin is a dynamic virtual representation of a physical object, process, or system that is connected to real-world data. In food manufacturing, this concept can allow processors to create a virtual representation of a fermentation vessel, dryer, pasteurization line, packaging operation, cold chain, or complete production facility.

The central value of a digital twin lies in its ability to connect physical observations with mathematical or computational models. Sensors installed on equipment continuously collect information such as temperature, pressure, humidity, flow rate, energy consumption and product characteristics. These data are transferred to the digital model, allowing it to represent the current state of the physical process.

Recent reviews describe applications of digital twins across food processing and supply chains, including monitoring, prediction, process optimization and quality assurance. Newer research also emphasizes integration with Artificial Intelligence (AI), Internet of Things (IoT) technologies, simulation and big-data analytics.

Fermentation is a particularly promising application. Biological systems are difficult to control because microbial growth can vary with feed composition and environmental conditions. A digital twin can combine sensor information with fermentation models to estimate biomass growth, substrate consumption, metabolite formation and contamination risk. Recent research specifically identifies opportunities for digital twins in monitoring microbial fermentation and supporting adaptive control.

Thermal processing is another suitable application. A virtual model can simulate heat transfer through a food product and estimate the effect of temperature-time combinations on microbial inactivation and quality degradation. Such a model could help engineers evaluate processing conditions without repeatedly performing physical trials.

Drying processes can also benefit from digital twins. Food dehydration involves simultaneous heat and mass transfer and is influenced by air temperature, velocity, relative humidity, product geometry and moisture distribution. A digital twin could estimate moisture loss and energy demand in real time. Operators could then modify drying conditions to achieve a desired final moisture content without excessive energy consumption.

Digital twins may also contribute to cold-chain management. Temperature fluctuations during transportation and storage can accelerate quality deterioration. A digital representation of the product and its environment can combine temperature histories with predictive quality models to estimate remaining shelf life. The concept becomes more powerful when combined with AI. A conventional digital model may simulate expected behavior, whereas an AI-enhanced digital twin can learn from historical production data and identify relationships that are difficult to model mathematically. This combination can improve predictive accuracy.

However, implementation is technically demanding. A digital twin requires reliable sensors, data infrastructure, communication systems, mathematical models and computational resources. Data interoperability is another major issue because equipment from different manufacturers may use different communication standards and data formats.

Biological variability presents an additional challenge. Food materials are not uniform engineering components. Two batches of the same crop can behave differently during processing. Therefore, digital twins need mechanisms for updating their models when raw-material properties change. Cybersecurity is also important. A highly connected food-processing facility may contain operational and commercial information that requires protection. Unauthorized access to control systems could potentially disrupt production or compromise food safety.

Standardization will be necessary for widespread adoption. Recent systematic research has proposed layered architectures involving perception, modeling, simulation and application

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components while identifying challenges related to data, models, processes and governance. Digital twins could ultimately support a shift from reactive to predictive manufacturing. Instead of correcting a quality problem after it occurs, processors could simulate potential outcomes before making operational changes. This may reduce trial-and-error experimentation, product losses, energy consumption and production variability.

CONCLUSION

The long-term development of digital twins may also include augmented reality, virtual reality, edge computing and autonomous decision systems. Research published in 2026 highlights the integration of digital twins with AI and immersive technologies as a pathway toward more intelligent and sustainable food-processing systems. Thus, digital twins represent an important bridge between physical food manufacturing and computational intelligence. Their successful application will depend on accurate models, reliable data, interoperability, cybersecurity and close collaboration between food scientists, engineers, data scientists and process operators.