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Perspective

Integrating Biotechnology Smart Sensors and Artificial Intelligence in Food Biomanufacturing

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DESCRIPTION

Food Bioprocess 4.0 is an emerging framework describing the integration of biological processing with advanced digital and automation technologies. It extends the principles of Industry 4.0 into food biotechnology by combining biological innovation, process monitoring, Artificial Intelligence (AI), automation and driven decision-making. A recent 2025 review describes Food Bioprocess 4.0 through three interconnected pillars: Biological technologies, physical process technologies and digital technologies.

The biological pillar includes precision fermentation, synthetic biology, metabolic engineering and related biotechnology. These approaches allow microorganisms to produce proteins, enzymes, organic acids, flavors, pigments and other food ingredients under controlled conditions. Genetic engineering can modify metabolic pathways to increase production efficiency or introduce new biosynthetic capabilities.

At the molecular level, genes responsible for desired metabolic functions can be introduced, deleted, or regulated. For example, altering the expression of genes associated with carbohydrate metabolism may influence the availability of precursor molecules for a target product. Gene-editing systems such as Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) can support targeted genetic modification, although regulatory and safety requirements must be considered.

The physical pillar includes Process Analytical Technology (PAT), smart sensors, automated equipment and Internet of Things (IoT) connectivity. Sensors can monitor temperature, pH, dissolved oxygen, pressure, biomass indicators and other variables during fermentation. Continuous monitoring provides information that traditional end-point laboratory testing cannot provide.

This real-time information becomes especially valuable in biological systems because microbial processes are dynamic. A small change in oxygen availability or nutrient concentration can alter growth and metabolite production. Smart sensors can detect such changes earlier, allowing corrective action. The digital pillar includes Artificial Intelligence (AI), Machine Lear -ning (ML), Digital Twins (DT), cloud computing and advanced data analytics. AI models can interpret complex datasets generated during fermentation and predict process outcomes. Digital twins can create virtual representations of bioreactors and production systems, enabling simulation and optimization.

The convergence of these three pillars can transform manufacturing from a sequential process into an interconnected system. A sensor detects a change in fermentation conditions, the digital system interprets the change and an automated controller can adjust feeding or aeration. This creates a feedback loop between measurement and action.

Automation can reduce repetitive manual activities. Automated sampling, cleaning, feeding and process control can improve reproducibility while reducing operator burden. However, automation does not eliminate the need for skilled personnel. Instead, workforce requirements shift toward data interpretation, process engineering, biotechnology and system management.

Quality assurance is another major advantage. Conventional food manufacturing frequently relies on testing the final product to confirm compliance. Food Bioprocess 4.0 aims to move toward proactive quality assurance in which deviations are detected during processing. This can reduce the probability of producing large quantities of nonconforming material. Sustainability may also benefit from intelligent process control. Optimizing nutrient feeding, aeration, water use, energy consumption and processing time can reduce resource requirements. Better process control may additionally decrease batch failures and material losses.

Nevertheless, significant challenges remain. The cost of sensors and digital infrastructure can be substantial. Data collected from different instruments may not be compatible. Biological

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variability can also make predictions less reliable than those for highly standardized engineering systems. Cybersecurity and data ownership are increasingly important as production systems become connected. Food manufacturers must protect operational data while ensuring that automated systems remain reliable.

Recent research emphasizes that Food Bioprocess 4.0 can combine precision fermentation, smart sensing, PAT, AI, digital twins and automated operations to shift food bio manufacturing toward adaptive and connected production. The future may involve increasingly autonomous bioprocessing systems capable of detecting deviations, predicting outcomes and adjusting operating conditions with limited human intervention. Food Bioprocess 4.0 therefore represents an important step toward intelligent, flexible and data-driven food biotechnology.

CONCLUSION

Future research should increasingly focus on integrated biorefineries, where one food side stream is separated into several valuable fractions. For example, a fruit-processing residue could potentially yield dietary fiber, phenolic extracts, pigments and fermentable carbohydrates rather than producing only one ingredient. Overall, upcycled food ingredients have the potential to transform food manufacturing from a predominantly linear system into a more resource-efficient circular system. Their long-term success will depend on combining nutritional science, food chemistry, biotechnology, process engineering, safety assessment, sustainability analysis and consumer research.