Toward Digital Twin-Driven Mushroom Cultivation: A Framework for Optimizing Growth, Yield, and Quality

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Mushroom cultivation is already a highly controlled biological production process. Temperature, relative humidity, carbon dioxide concentration, ventilation, substrate conditions, watering, and cultivation time are carefully managed, yet most strategies still rely on predefined setpoints and empirical experience. In this editorial, we argue that digital twins could provide the next step: not another monitoring platform, but a continuously updated virtual representation of the crop-production system. Such a twin should combine environmental measurements, substrate information, crop development, historical production data, and predictive models to estimate the current crop state and evaluate alternative cultivation strategies. The objective would not simply be better environmental control, but adaptive optimization of yield, quality, resource consumption, and production time. Mushroom cultivation therefore offers an unusually suitable environment in which digital twins could evolve from an engineering concept into a practical tool for biological production.

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Introduction

Commercial mushroom cultivation is already close to what many other agricultural sectors are trying to achieve: production takes place in a controlled environment, the cultivation cycle is relatively short, and many influential variables can be measured and modified. In *Agaricus bisporus* production, temperature, humidity, CO_2 concentration, ventilation, watering, compost properties, casing conditions, and cultivation stage interact to determine crop development (Baars *et al*. 2020).

Sensors, IoT platforms, image analysis, and automated climate control are increasingly available for mushroom farms (Guragain *et al*. 2024; Badoni and Siddiqui 2025). However, better monitoring does not automatically mean better understanding. Maintaining a prescribed temperature or CO_2 concentration remains essentially a reactive strategy, even if the measurement and control are fully automated.

In our view, the next step should not be another layer of automation. It should be a digital twin capable of learning how a particular crop responds to its cultivation history and using this knowledge to predict what should happen next.

The Crop, Not the Growing Room, Should Be the Twin

A digital twin should not simply reproduce the environmental state of a growing room. The growing room is only the container. The real system of interest is the crop-production system: substrate or compost, casing layer, mycelium, developing fruiting bodies, microclimate, and their interactions over time (Purcell and Neubauer 2023).

This distinction is important. A sensor system may report that air temperature is 18 °C and relative humidity is 90%. A digital twin should attempt to answer a different question: what do these conditions mean for this particular crop at its present stage?

The twin should therefore combine three information streams. The first describes the initial biological and technological state, including strain, substrate composition, moisture, casing properties, filling conditions, and initial colonization. The second represents cultivation history, including temperature, humidity, CO_2, ventilation, watering, and other controllable variables. The third describes the observed crop response, such as mycelial development, pinning, growth rate, fruiting-body number and distribution, size, maturity, uniformity, and final yield.

The purpose is not to collect more data for their own sake. It is to connect: initial state → cultivation history → biological response. Only then does the digital representation begin to describe the crop rather than merely its surroundings.

From Predefined Recipes to Predictive Cultivation

Most commercial cultivation still relies, to some extent, on production recipes (Badoni and Siddiqui 2025). Environmental conditions are changed according to experience and developmental stage. These recipes may be sophisticated, but they remain largely predefined.

A digital twin changes the direction of reasoning. Instead of asking only what is happening now, it should estimate what is likely to happen if the cultivation strategy is changed.

Should ventilation be increased earlier? Would a temporary temperature modification accelerate development without reducing quality? Could a different watering strategy improve uniformity? Would a small reduction in expected yield be acceptable if it shortened the cycle or reduced energy consumption?

Such questions cannot be answered satisfactorily by fixed setpoints because mushroom cultivation is dynamic. The optimal conditions today may not be optimal tomorrow, and two nominally identical crops may respond differently because of substrate variability, microbial activity, airflow, equipment, or previous environmental history (Baars *et al*. 2020).

The optimization target should therefore not be a single temperature, humidity, or CO_2 value. It should be an optimal trajectory of cultivation conditions that changes with the estimated biological state of the crop.

This is where digital twins become particularly attractive. In other engineering applications, experimentally supported digital twins already combine measurements, predictive models, model updating, and optimization within a common framework (Szymczak-Graczyk *et al*. 2025; Garbowski and Karasiewicz 2026). Similar ideas increasingly connect mechanistic models, surrogate modelling, machine learning, and numerical optimization (Garbowski *et al*. 2026). Mushroom production provides a compelling biological system in which this philosophy could be tested.

Optimization Should Mean More than Maximizing Yield

Maximum yield is an obvious objective, but it should not be the only one. A commercial grower may accept slightly lower total production if this results in better size uniformity, higher product quality, shorter cultivation time, lower energy demand, reduced water use, or more predictable harvesting. Different markets may also prefer different combinations of mushroom size, maturity, and quality.

A useful mushroom digital twin should therefore support multi-objective decisions. Yield, biological efficiency, product quality, cultivation time, water and energy consumption, substrate utilization, and economic performance could all be considered simultaneously.

More importantly, optimization should become crop-specific and facility-specific. Rather than asking, "What conditions are optimal for *Agaricus bisporus*?", the practical question is: "What conditions are optimal for this crop, in this growing room, at this moment?"

Every cultivation cycle could improve the answer. Predictions would be compared with actual crop development and final production data, and the resulting errors could be used to update the model. Each crop would therefore produce not only mushrooms, but also information for improving the next cycle.

What Remains Difficult?

The major obstacle is unlikely to be the availability of sensors. The harder problem is linking measurable environmental conditions with a biological state that cannot always be observed directly.

Mushrooms respond not only to present conditions but also to their history (Baars *et al*. 2020). The same temperature and humidity can lead to different outcomes depending on substrate, developmental stage, previous stress, spatial position, or other biological factors. Even in *A. bisporus*, some mechanisms controlling fruiting and crop development remain incompletely understood (Baars *et al*. 2020).

For this reason, neither purely mechanistic nor purely data-driven models are likely to be sufficient. Hybrid models appear more realistic: biological and physical knowledge can provide structure, while production data can continuously correct the prediction.

Uncertainty must also be treated as part of the digital twin rather than as an inconvenience. A biological model should not merely predict that one strategy is better than another. It should indicate how confidently it can make that claim.

Conclusions

Mushroom production already contains most of the technical ingredients required for digital twins: controlled environments, repeated production cycles, dense sensor information, measurable outputs, and increasing automation. What remains missing is their integration into a predictive model that follows the biological state of the crop and supports decisions throughout the cultivation cycle.

The purpose of such a system should not be to replace grower experience. It should make that experience more predictive, transferable, and testable by allowing alternative cultivation strategies to be evaluated virtually before they are imposed on the physical crop.

The transition is therefore not simply from manual control to automation. It is from predefined recipes to adaptive cultivation. Sensors can describe the growing room. A digital twin should understand the crop.

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