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AI, IOT, CLOUD COMPUTING AND DIGITAL TWIN INTEGRATION FOR SMART EDUCATIONAL CAMPUSES: A REVIEW

Radha Balkrushna Ghodke^{*1}, Dr. Jeetendra Singh Yadav²

¹M.Tech Scholar, Department of Computer Science and Engineering, Bhabha University,
Bhopal, India.

²Associate Professor, Department of Computer Science and Engineering, Bhabha University,
Bhopal, India.

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***Corresponding Author: Radha Balkrushna Ghodke**

M.Tech Scholar, Department of Computer Science and Engineering, Bhabha University,
Bhopal, India.

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ABSTRACT

Smart educational campuses are increasingly being developed as connected environments in which physical facilities, people, services, and operational resources generate data for coordinated management. This review examines the complementary roles of Internet of Things (IoT), Artificial Intelligence (AI), cloud computing, and Digital Twin (DT) technology in such environments. The review is derived from the literature base of the completed M.Tech thesis and is strengthened with recent peer-reviewed work on smart-campus integration and campus Digital Twin implementation. The literature indicates that IoT provides continuous sensing, cloud platforms support shared storage and processing, AI converts observations into predictions and analytical indicators, and Digital Twins maintain a contextual digital representation of campus assets. Recent research also demonstrates practical campus implementations involving energy, occupancy, room usage, facility management, and sensor integration. However, the literature continues to identify interoperability, data governance, privacy, cybersecurity, scalability, synchronization, and deployment cost as important challenges. A recurring limitation is that many studies emphasize a single technology or a narrow application rather than an integrated educational-campus workflow. The review therefore organizes the field around five themes: smart-campus evolution, enabling technologies, integrated architectures, application domains, and implementation challenges. The review concludes by identifying a research need for simulation-supported, modular frameworks that connect sensing, centralized data handling,

predictive analytics, and continuously updated digital representations while keeping live-data validation as a necessary next step.

KEYWORDS: Smart Campus, Digital Twin, Artificial Intelligence, Internet of Things, Cloud Computing, Machine Learning, Campus Management, Predictive Analytics.

1. INTRODUCTION

Universities operate complex infrastructures that include academic buildings, classrooms, laboratories, libraries, hostels, administrative facilities, parking areas, utilities, and shared services. Traditionally, these functions have often been managed through separate applications, periodic inspections, departmental records, and manually coordinated activities. Such arrangements can provide information about individual functions but do not necessarily provide one consistent operational view of the campus. The smart-campus concept responds to this challenge by connecting physical infrastructure with digital technologies that can acquire, process, interpret, and represent operational information.

The development of smart educational campuses has followed the broader evolution of digital infrastructure. Networked information systems first improved administrative processes, followed by cloud platforms and connected sensing. IoT expanded the volume and frequency of operational observations, while AI introduced pattern recognition and prediction. Digital Twin technology adds another layer by maintaining a digital counterpart of a physical or simulated system and linking its state to incoming information. In a campus setting, this creates an opportunity to move from isolated monitoring toward a shared digital environment for observation, analysis, and scenario-based management.

Recent scholarship supports this integrated direction. Haggag et al. conducted a 2025 survey of advanced technologies for sustainable Smart Campus development and examined AI, IoT, Digital Twins, Big Data, and related technologies together. Their review identified operational and sustainability opportunities while also highlighting integration complexity, privacy, security, and investment requirements. A separate systematic review by Alnaser et al. examined AI-powered Digital Twins and IoT across smart-city and sustainable-building applications, reinforcing the importance of data-driven Digital Twin architectures beyond manufacturing. These studies provide a useful basis for examining how the same technology stack can be adapted to higher-education campuses. [1], [2], [3]

This paper reviews the technology relationships that are most relevant to AI-powered Digital Twin frameworks for educational campuses. Rather than treating the technologies as

independent subjects, the review focuses on their information pathway: sensing, data handling, analytics, digital representation, and management support.

2. Review Scope and Approach

The review follows the literature structure used in the completed thesis, with particular attention to work published during 2021–2026 on smart campuses, IoT monitoring, AI-based analysis, cloud computing, Digital Twins, facility management, and intelligent infrastructure. The thesis literature review was organized around the question of how sensing, analytics, digital representation, and decision support can be connected in an educational-campus environment. For this paper, that material is synthesized into thematic findings rather than reproduced as a study-by-study list.

The review also considers several externally verified recent publications that provide direct evidence for the state of the field. Haggag et al. (2025) provide a dedicated Smart Campus technology survey; Roda-Sanchez et al. (2024) report a real-world Smart Campus Digital Twin at the University of Murcia; and Muñoz Pavón et al. (2025) describe a BIM-based Digital Twin implemented at the Universidad Politécnica de Madrid. Foundational Digital Twin reviews by Kritzinger et al. and Fuller et al. are used to clarify the distinction between digital models, digital shadows, and more tightly connected Digital Twin concepts.

The review is qualitative and thematic. It does not claim a new bibliometric count or a systematic meta-analysis. The purpose is to identify recurring technological functions, application areas, integration requirements, and research gaps that are directly relevant to the development of smart educational-campus Digital Twins.

Table I. Comparison of representative studies on smart-campus and Digital Twin technologies.

Study	Technology / Focus	Application	Main Contribution	Gap / Limitation
Haggag et al. (2025) [1]	AI, IoT, DT, Big Data	Smart Campus sustainability	Integrated survey of advanced technologies	Integration, privacy, security and investment challenges
Roda-Sanchez et al. (2024) [2]	DT, IoT, Fog–Edge–Cloud, 5G	23-building university campus	Energy, occupancy, room-use and anomaly analytics	Specific campus infrastructure
Muñoz Pavón et al. (2025) [3]	BIM, IoT, Cloud, DT	University facility management	BIM-linked Digital Twin for campus	Interoperability and implementation

			management	effort
Alnaser et al. (2024) [4]	AI + DT + IoT	Smart cities / sustainable buildings	Reviews AI-enabled DT and sustainability	Limited higher-education validation
Kritzinger et al. (2018) [5]	DT concepts	Manufacturing	Digital Model, Shadow and Twin distinction	Not campus-specific
Fuller et al. (2020) [6]	DT enabling technologies	Cross-domain	Technologies, challenges and research issues	Broad rather than campus-focused
Lu et al. (2020) [7]	DT-driven systems	Smart manufacturing	Reference model and research issues	Manufacturing context
Tao et al. (2019) [8]	DT and CPS	Industry 4.0	DT–CPS relationship	Industrial emphasis
Hakimi et al. (2024) [9]	DT + facility management	Buildings / FM	Maps predictive maintenance and real-time DT themes	Broader FM literature
Domínguez-Bolaño et al. (2024) [10]	IoT monitoring	University campus	Five real-world campus use cases	Not a full DT workflow
AlBalkhy et al. (2024) [11]	DT in built environment	Buildings / infrastructure	DT layers, applications and challenges	Broader built-environment scope
Céspedes-Cubides & Jradi (2024) [12]	Building DT	Energy efficiency	Reviews DT for operational energy efficiency	Building-level focus
Walczyk & Ożadowicz (2024) [13]	BIM, DT, distributed IoT	Smart buildings	Interoperability and automation review	Building automation focus
López-Goyez et al. (2026) [14]	Smart Campus, AI, IoT, Big Data	Higher education	Systematic review of 45 studies and key gaps	Not focused specifically on AI-powered campus DT

3. Evolution of Smart Educational Campuses

The first stage of campus digitalization focused on institutional information systems such as admissions, examinations, finance, library management, and communication. These systems reduced manual work but generally remained function-specific. Cloud computing then improved centralized access, scalability, and data sharing. The emergence of IoT changed the nature of campus information by allowing physical conditions to be captured repeatedly from classrooms, laboratories, libraries, utilities, parking spaces, and equipment.

The next step was analytical. Once campuses began producing frequent observations, data collection alone became insufficient. Machine-learning methods could identify relationships,

classify conditions, detect unusual patterns, and estimate future demand. AI therefore provides a bridge between raw observations and management information. Digital Twin technology extends this bridge by associating observations with digital entities representing the relevant physical facilities. The combination creates a cycle in which operational observations can update a digital state, analytical models can interpret the state, and the resulting information can support planning or intervention.

Kritzinger et al. emphasized that Digital Model, Digital Shadow, and Digital Twin should not be treated as identical concepts. Fuller et al. similarly described Digital Twins in terms of data integration between physical and virtual systems and discussed enabling technologies and open research issues. These distinctions matter for campus research because a static 3-D model or a dashboard is not automatically a Digital Twin. The strength of a campus Twin lies in the relationship between the represented asset, its operational data, and the updating mechanism. [5], [6]

4. Internet of Things as the Sensing Layer

IoT provides the physical information-acquisition layer of a smart educational campus. Temperature and humidity sensors can describe indoor environmental conditions; occupancy sensors can indicate how spaces are being used; smart meters can capture electricity consumption; water meters can track consumption; air-quality devices can provide environmental indicators; and equipment-status sensors can indicate operating conditions. When these observations are time-stamped and associated with buildings or rooms, they form the raw information required by higher layers of the architecture.

The literature reviewed in the thesis repeatedly identifies IoT as a foundation for campus monitoring. Research on academic infrastructure has used distributed sensing to reduce reliance on periodic manual inspection and to improve visibility across multiple locations. However, IoT also introduces practical requirements. Device interoperability, communication reliability, cybersecurity, privacy, sensor maintenance, and the management of high-volume data streams become more important as the number of connected assets increases. [1], [2]

The sensing layer should therefore be designed with the later analytical and Digital Twin requirements in mind. Data should contain adequate timestamps, facility identifiers, consistent units, and quality checks. Without this structure, later AI models may receive incomplete or inconsistent inputs and the Digital Twin may be unable to associate observations with the correct digital entities. The layered IoT structure relevant to smart educational campuses is summarized in Fig. 1.

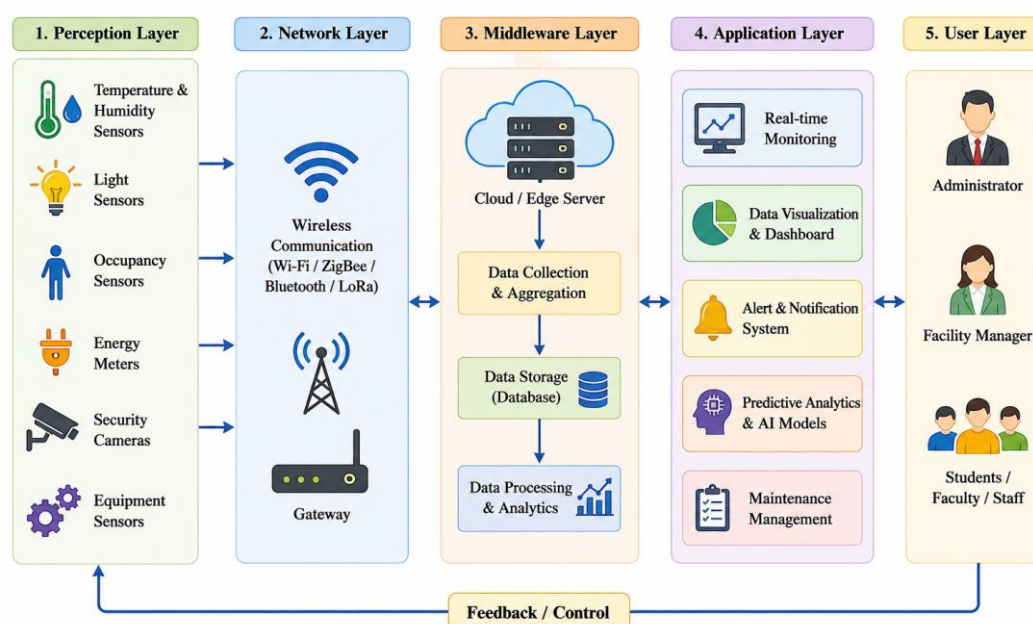


Fig. 1. Layered IoT architecture for smart educational campuses.

5. Cloud Computing and Data Management

Cloud computing acts as a shared environment for storing, organizing, and processing campus information. In a multi-building campus, data may originate from hundreds or thousands of devices. A common data environment reduces the dependence on isolated departmental repositories and provides a central location from which analytics and Digital Twin services can retrieve prepared information. [10], [13]

The thesis framework places cloud computing between IoT acquisition and AI/Digital Twin functions. This arrangement supports a sequential information flow: sensor observations are transferred to the cloud, checked and prepared, supplied to the AI layer, and then associated with Digital Twin entities. The cloud layer can also provide scalability as additional buildings, sensors, or services are added.

Cloud architecture does not eliminate data-management challenges. Data quality, access control, interoperability, network availability, latency, and privacy must be addressed. For applications requiring rapid synchronization, edge or fog processing may also complement cloud services. The real-world University of Murcia implementation, for example, combined sensor infrastructure with Fog–Edge–Cloud computing and a private 5G network, illustrating that campus Digital Twins may require multiple computational levels rather than cloud-only processing. [2], [4], [6]

6. Artificial Intelligence and Machine Learning

AI supplies the analytical capability required to convert operational observations into predictive or decision-support information. Campus applications can use machine learning for energy prediction, occupancy estimation, anomaly detection, equipment-condition analysis, scheduling support, and resource planning. AI becomes particularly useful when historical observations are combined with current sensor information. [4], [9], [14]

The literature indicates that AI should be selected according to the task and data rather than treated as a universal solution. Tree-based methods can handle mixed operational variables and nonlinear relationships, while other tasks may require time-series, deep-learning, or hybrid approaches. The completed thesis uses Random Forest as the primary machine-learning model for the simulation study. This choice is application-specific and is used to establish a measurable prediction baseline rather than to claim that Random Forest is universally optimal. [4], [6]

AI also changes the role of the Digital Twin. A Twin that only displays current sensor values provides descriptive visibility. When predictions, anomaly indicators, or estimated future conditions are added, the digital representation can support forward-looking analysis. This creates a progression from monitoring to prediction and, potentially, to scenario-based decision support.

7. Digital Twin for Campus Management

A campus Digital Twin can represent buildings, rooms, laboratories, utilities, equipment, and other operational entities as connected digital objects. Incoming information is associated with the relevant entity so that the digital state remains aligned with observed conditions. This provides a common context in which energy, occupancy, environmental, and equipment information can be examined together. [11], [12]

The value of this approach is demonstrated by real-world campus studies. Roda-Sanchez et al. developed a Digital Twin for 23 buildings at the University of Murcia and combined sensor data, external data sources, and analytics. Their work included models for energy consumption, building occupancy, room usage, solar energy, and anomaly detection. Muñoz Pavón et al. reported a BIM-based Digital Twin for the Civil Engineering School at Universidad Politécnica de Madrid, linking BIM, IoT, cloud computing, live sensor data, space reservation, and asset management. These implementations show that campus Digital Twins can move beyond visualization toward operational functions [2], [3]. A corresponding Digital Twin-oriented architecture is illustrated in Fig. 2.

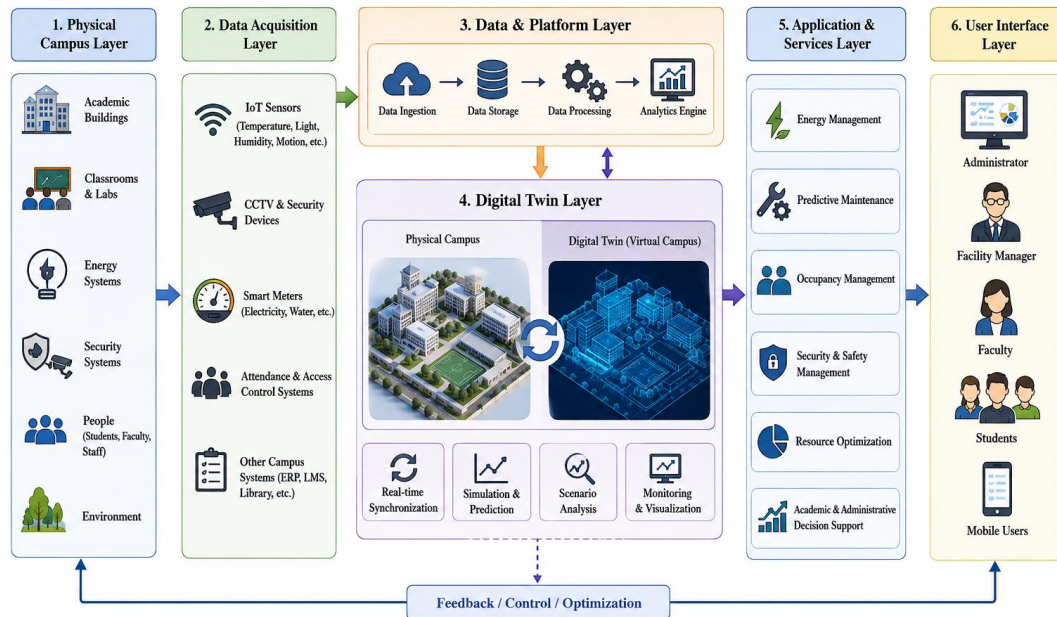


Fig. 2. Digital Twin architecture for smart educational campuses.

At the same time, the literature demonstrates that synchronization is central to the concept. A virtual representation becomes less useful when its state is delayed, incomplete, or disconnected from the source system. Consequently, synchronization delay, data freshness, communication reliability, and semantic consistency should be considered evaluation variables rather than purely implementation details. [11], [13]

8. Integration of AI, IoT, Cloud and Digital Twin

The central architectural finding from the reviewed literature is that the four technologies perform different but complementary functions. IoT captures observations; cloud infrastructure provides shared data handling; AI identifies patterns and generates predictions; and the Digital Twin maintains a contextual representation of campus assets. Their integration is therefore more meaningful than the isolated deployment of any one component. [1], [2], [4], [6]

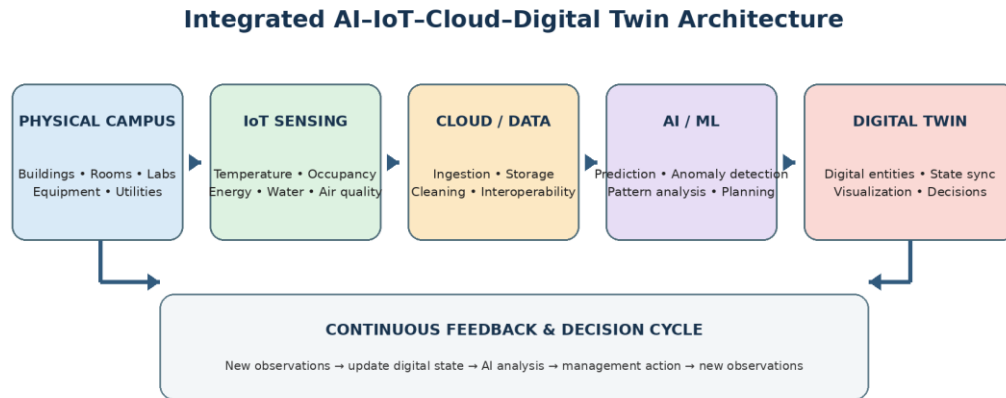


Fig. 3. Integrated AI-IoT-Cloud-Digital Twin architecture for smart educational campuses.

A generalized information pathway can be expressed as: Physical/Simulated Campus → IoT Sensing → Cloud Data Handling → AI Analytics → Digital Twin Synchronization → Visualization and Decision Support. The pathway is cyclical because new observations continuously update the digital state and can subsequently influence the next analytical cycle. This architecture also supports modular expansion: new sensors can be added at the acquisition layer, new analytical models at the AI layer, and new facilities as Digital Twin entities.

The main benefit of this architecture is a shared operational context. Instead of examining energy, occupancy, environmental conditions, and equipment information in separate systems, the information can be associated with the same campus entities. This creates a basis for coordinated management and scenario analysis. However, the integration itself introduces additional dependencies, so architecture quality must be evaluated in terms of data consistency, latency, interoperability, scalability, security, and model reliability.

9. Major Application Areas

- Energy management: monitoring building consumption, identifying high-demand periods, forecasting demand, and examining the effect of operational changes. [15], [17], [18], [21]
- Occupancy and space management: tracking classroom and laboratory use, identifying demand patterns, and supporting scheduling or allocation.
- Facility management: associating equipment and building information with digital entities for maintenance and operational supervision.

- Environmental monitoring: combining temperature, humidity, air quality, and related observations with facility information.
- Predictive maintenance: using historical and current operational data to identify unusual equipment behaviour before failure.
- Safety and security support: integrating relevant status information into a common digital environment while applying appropriate privacy and access controls.
- Sustainability management: extending the Twin to water use, renewable-energy generation, carbon indicators, and other environmental measures.

Table II. Major application areas of AI-enabled Digital Twin systems in smart educational campuses.

Application	Primary Data	AI / DT Role	Management Use
Energy management	Smart-meter and building load data	Demand prediction and scenario analysis	Energy scheduling and efficiency planning
Occupancy & space	Occupancy sensors and schedules	Occupancy estimation and demand analysis	Room allocation and utilization
Facility management	Equipment status and asset history	Anomaly detection and predictive maintenance	Maintenance prioritization
Environmental monitoring	Temperature, humidity, air quality	Condition prediction and threshold detection	Comfort and indoor-environment control
Water management	Flow and consumption data	Pattern analysis and anomaly detection	Leak detection and conservation
Safety & security support	Infrastructure/status information	Event detection and contextual visualization	Situational awareness with access control
Sustainability	Energy, water, renewables, carbon indicators	Forecasting and integrated scenarios	Sustainability assessment and planning

10. Research Gaps and Challenges

Despite rapid development, several gaps remain. First, interoperability is a recurring issue because campuses contain heterogeneous sensors, software systems, databases, and communication technologies. Second, data governance becomes important when continuous observations are combined across buildings and user-related activities. Third, privacy and cybersecurity must be addressed because connected infrastructure increases the number of digital interfaces. Fourth, synchronization must remain reliable when network conditions

vary. Fifth, many studies demonstrate a specific application rather than a complete end-to-end campus workflow. [10], [11], [14]

Another gap concerns validation. Simulation is useful for early-stage architecture testing because it permits controlled experimentation without immediate deployment of physical infrastructure. However, simulated observations cannot fully reproduce sensor noise, network interruptions, missing data, behavioural variability, or institutional operating constraints. Therefore, a simulation-based framework should be considered a development and validation stage rather than a substitute for field deployment. [11], [14]

The literature also suggests that future research should examine the interaction between predictive models and Digital Twin decisions more explicitly. A prediction becomes more useful when it is linked to a facility, visualized in context, and connected to a possible management action. This points toward decision-oriented Twins rather than Twins that are limited to monitoring and visualization.

Table III. Key research gaps and corresponding research needs.

Challenge / Gap	Observed Issue	Research Need
Interoperability	Heterogeneous sensors, databases and software	Common data models, APIs and semantic mappings
Synchronization	Latency, missing data and network variation	Edge/fog support and synchronization metrics
AI integration	Different tasks require different models and data quality	Task-specific model comparison and explainable analytics
Privacy & cybersecurity	Continuous connected-campus data increases exposure	Security-by-design and privacy-preserving methods
Validation	Many studies are prototypes, simulations or single-campus cases	Long-term multi-building field validation
Scalability & cost	More devices and buildings increase complexity	Modular architecture and lifecycle cost evaluation

11. Research Directions

Future smart-campus research can proceed along several connected directions. Live deployment can validate synchronization and prediction using actual campus data. Additional machine-learning and deep-learning models can be compared against baseline algorithms for different prediction tasks. Edge and fog computing can be incorporated where low latency is required. BIM and GIS can strengthen the spatial representation of facilities. Renewable-energy systems, battery storage, water consumption, and carbon indicators can be added to support sustainability analysis. Security-by-design approaches should be incorporated across device, network, cloud, AI, and Digital Twin layers.

Another useful direction is the development of standardized campus data models and interfaces. Common schemas for buildings, rooms, equipment, sensors, occupancy, energy, and environmental observations could reduce integration effort and make Digital Twin components more reusable across institutions. Such standardization would also improve the reproducibility of research results and facilitate comparison among campus implementations.

12. CONCLUSION

The reviewed literature shows a clear progression from isolated digital services toward connected smart-campus environments in which sensing, analytics, and digital representation are increasingly integrated. IoT provides the observational foundation, cloud computing supports shared data handling, AI contributes prediction and analytical interpretation, and Digital Twin technology provides a contextual digital representation of campus operations. Recent real-world implementations demonstrate that these technologies can be combined for energy, occupancy, room usage, facility management, and other campus functions. Nevertheless, interoperability, privacy, cybersecurity, synchronization, scalability, cost, and live-data validation remain important research and implementation considerations.

For the completed M.Tech thesis, these findings support the use of an integrated AI–IoT–cloud–Digital Twin architecture and the simulation-based evaluation strategy. The review also clarifies the boundary of the contribution: a controlled simulation can demonstrate the behaviour of the proposed workflow, while field deployment is required to establish performance under real campus conditions.

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