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(57) Abstract :
The global push for sustainable infrastructure has heightened the need for intelligent thermal management in buildings, which account for nearly 40% of global energy consumption, with HVAC systems alone responsible for over 50% of that. This paper introduces a Smart Thermal Insulation System (STIS) enhanced with Artificial Intelligence (AI) and Machine Learning (ML) algorithms for automated control and monitoring of indoor environments. The proposed system integrates IoT-enabled sensors, adaptive insulation materials (e.g., phase change materials with thermal conductivity of 0.18 W/m·K, and silica aerogels with 0.013 W/m·K), and AI-driven control logic to optimize energy usage while maintaining occupant comfort. STIS utilizes a network of temperature, humidity, $CO_2$, and occupancy sensors to collect real-time data. Machine learning models such as Random Forest for anomaly detection and Reinforcement Learning (Q-learning) for energy optimization are employed to predict and adjust insulation behavior. The system was deployed in two different test environments: a traditional building (control site) and a smart STIS-enabled building (test site), both located in Chennai, India. Experimental results over a 90-day summer monitoring period showed that the STIS-enabled building reduced HVAC energy consumption by 38.7%, compared to the traditional counterpart. Internal temperatures were stabilized within ±1.5°C of the target range (23–25°C), despite external temperature fluctuations between 31°C and 43°C. Furthermore, predictive maintenance alerts reduced system downtime by 22%, enhancing operational continuity. Compared to conventional passive insulation or programmable thermostats, STIS adapts to real-time conditions, forecasts, and occupancy patterns, offering greater efficiency and user autonomy. For instance, during peak occupancy, the system automatically pre-cooled zones with high footfall, avoiding unnecessary energy spikes. In conclusion, STIS demonstrates a practical, AI-driven pathway for reducing building energy use, cutting costs by 20–25% annually, and supporting smart city goals through intelligent automation and sustainability.

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