

## ENHANCING ENERGY EFFICIENCY IN GREENHOUSES USING PCM-BASED THERMAL STORAGE SYSTEMS INTEGRATED WITH ARTIFICIAL INTELLIGENCE AND BIG DATA TECHNOLOGIES

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**Abstract:** This paper investigates the role of artificial intelligence (AI) and Big Data technologies in enhancing energy efficiency in greenhouses equipped with thermal storage systems based on phase change materials (PCMs). Research indicates that AI can be utilized to forecast temperature fluctuations and optimize PCM performance, while Big Data supports identifying the most efficient solutions through analysis of large datasets. Literature reviews suggest that such integrated systems can reduce energy consumption by 17–25%. However, their effectiveness varies with climatic conditions and greenhouse design, highlighting the need for system adaptation to specific environments.

**Keywords:** PCM, greenhouse, solar energy, thermal storage, AI, Big Data

### Introduction

In recent years, ecological sustainability and energy efficiency have become pressing global concerns. Rapid population growth, urbanization, and the increasing demand for high-yield agriculture have significantly expanded the use of greenhouses. As a result, integrating energy-saving technologies into greenhouse systems has become increasingly necessary, as heating and cooling consume substantial energy resources.

In this context, thermal storage systems based on phase change materials (PCMs) offer an effective solution to improve greenhouse energy efficiency. PCMs store and release thermal energy by changing their physical phase. However, these systems may not function optimally on their own due to environmental variables such as temperature, solar radiation, humidity, and local climate.

Advanced technologies such as artificial intelligence (AI) and Big Data analytics have emerged as powerful tools to manage and optimize such complex systems. This paper explores how PCM-based systems, managed using AI and Big Data, can enhance energy efficiency in greenhouses.

### Main Content

#### 1. Phase Change Materials (PCMs) and Their Energetic Role

PCMs are materials capable of absorbing or releasing significant amounts of thermal energy during phase transitions (e.g., from solid to liquid and vice versa). This process helps stabilize the internal temperature of greenhouses.

Common PCM types include:

Organic materials: paraffins, fatty acids

Inorganic materials: salt hydrates

Eutectic mixtures: combinations of multiple compounds

In greenhouses, PCMs help prevent temperature drops during nighttime or early mornings by absorbing excess heat during the day and releasing it when needed. However, since these systems are passive and temporary in nature, they are not always effective when operating independently. Therefore, smart control systems are required.

## 2. Role of Artificial Intelligence (AI)

AI provides advanced tools for data analysis, prediction, and real-time decision-making. Its role in managing PCM systems includes:

Temperature forecasting: Machine learning (ML) models, especially artificial neural networks (ANNs), can predict both internal and external temperature variations.

Real-time control: AI can determine optimal melting and freezing times for PCMs, enhancing energy efficiency.

Adaptive learning: AI systems can learn and adjust to different seasons or climatic zones, allowing dynamic PCM operation.

For example, Zhang et al. (2019) demonstrated that using AI to manage PCM-based greenhouse systems resulted in up to 23% energy savings.

## 3. Role of Big Data Analytics

Big Data technologies process vast volumes of dynamic, varied data. In greenhouses, typical datasets include:

- Temperature and humidity readings
- Solar radiation levels
- Current PCM state
- Plant growth data
- Electricity consumption

These data are used to train AI models and optimize decision-making. Big Data analytics help determine the most suitable PCM types for various climates and greenhouse designs.

For instance, Kumar & Singh (2020) analyzed more than 20 PCM types across different regions in India, ranking them based on energy savings, efficiency, and cost-effectiveness.

## 4. Advantages of the Integrated Approach

Combining AI, Big Data, and PCM technologies offers several benefits:

- 17–25% energy savings
- Stable microclimate for optimal plant growth
- Reduced human intervention via automated control
- Design customization based on regional climate

However, these systems require initial investment and technical expertise for successful implementation.

## 5. Limitations and Future Prospects

Despite their advantages, such advanced systems face some limitations:

- Climatic dependency (e.g., snowy or very hot climates)
- Inefficiency if PCM's melting/freezing point is poorly selected
- Errors due to inaccurate AI model training
- High infrastructure requirements for storing and processing large data volumes

Future research should focus on developing low-cost, eco-friendly PCM alternatives and improving AI model accuracy and system adaptability.

## Conclusion

The analysis above shows that PCM-based thermal storage systems can be effectively managed using AI and Big Data technologies. This integrated approach allows greenhouses to optimize

energy consumption, create ideal plant growth conditions, and reduce human dependency through automation.

However, successful implementation depends on tailoring the technologies to specific greenhouse designs and regional climates. Factors such as PCM selection, AI algorithm quality, and data infrastructure significantly influence overall performance. Therefore, consistent research in this direction remains essential.

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