SYSTEM OUTPUTS AND RESULTS

This section presents the key outputs generated by the proposed smart freezer system, as observed through the hardware layer, cloud dashboards, and AI/ML analytics. The outputs validate the correct functioning of sensing, control, monitoring, and intelligence components of the system.

The system outputs are broadly classified into:

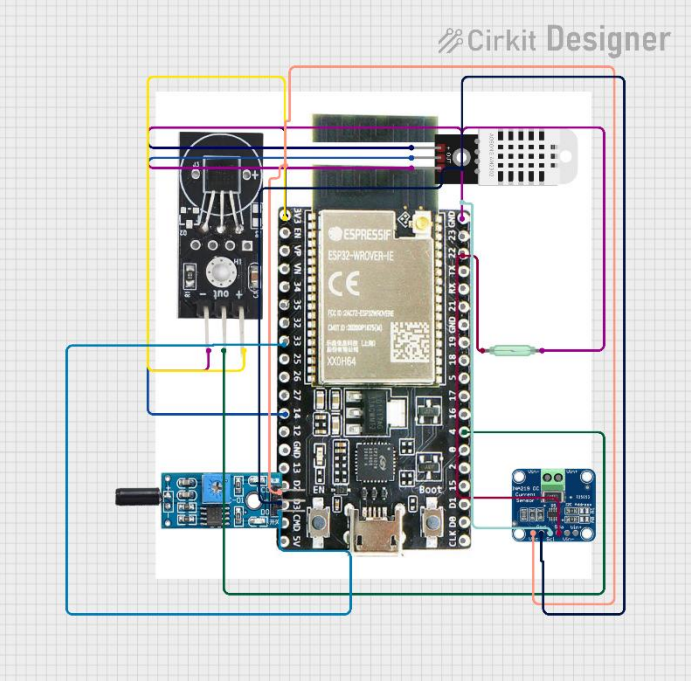
1. Hardware and Sensor Outputs
2. Control and Actuator Outputs
3. Dashboard Visualization Outputs
4. AI and Machine Learning Outputs

Hardware and Sensor Outputs

The Edge IoT layer continuously acquires real-time data from multiple sensors integrated within the freezer. These raw hardware outputs form the foundation for control and analytics.

Key Sensor Outputs

- Cabinet temperature (°C)
- Evaporator temperature (°C)
- Humidity (%)
- Door open/close status
- Compressor current and power (A, W)
- High-side and low-side pressure values
- Suction and discharge line temperatures
- Vibration levels



These values are sampled, filtered, and packaged by the ESP32 before being transmitted to the cloud.

Control and Actuator Outputs

Based on the processed sensor data and inferred load conditions, the control logic generates real-time actuator outputs.

Control Outputs Generated

- Compressor speed (RPM) – dynamically adjusted based on load index

- EEV step position – modulated to maintain optimal superheat
- Condenser fan speed (PWM duty cycle)
- Safety relay status – ON/OFF during fault conditions

These outputs demonstrate the system's ability to **adaptively regulate freezer operation** rather than operating in fixed ON/OFF cycles.

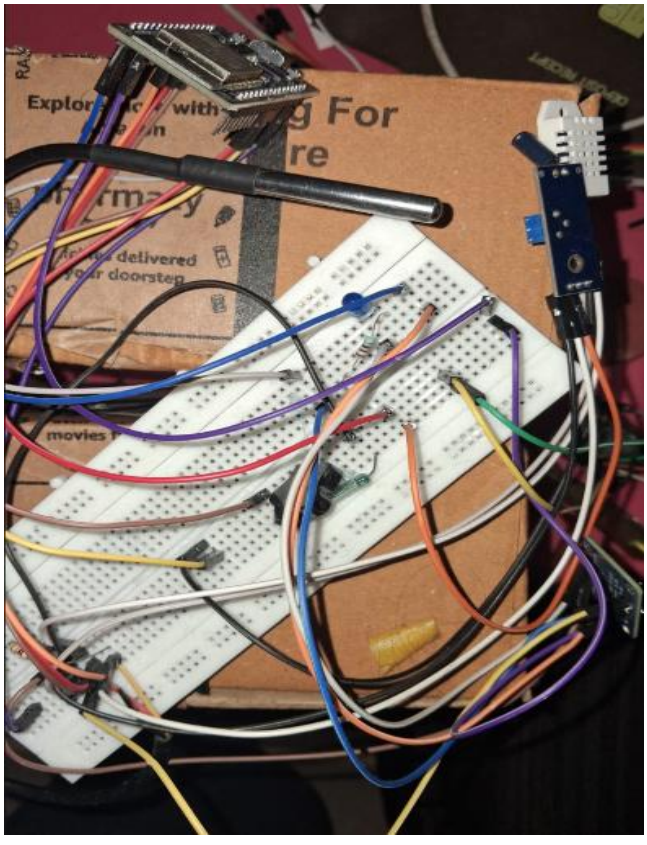
Dashboard Visualization Outputs

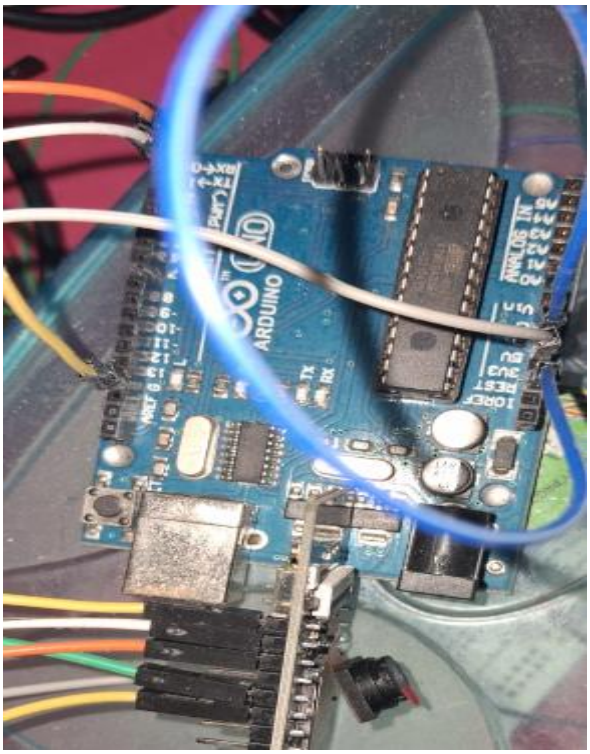
All sensor and control outputs are visualized in real time using **Node-RED / Grafana dashboards**, enabling remote monitoring and analysis.

Dashboard Displays Include

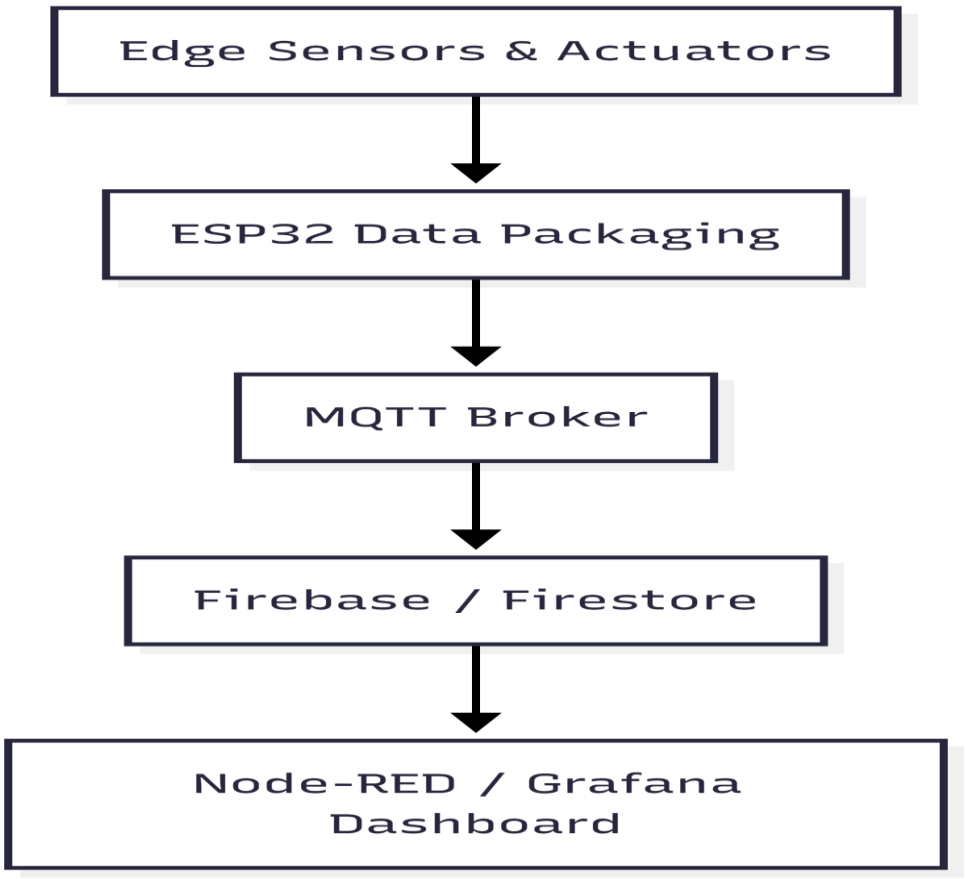
- Live temperature gauges and trends
- Power and current graphs
- Door event indicators
- Compressor RPM and fan speed visualization
- Safety and fault status indicators
- Timestamped data logs

The dashboard acts as the **human–machine interface (HMI)** of the system, providing operational transparency and decision support.





Dashboard Output Flow Architecture



AI and Machine Learning Outputs

The AI layer generates high-level outputs that extend beyond basic monitoring, enabling intelligence-driven insights.

Vision-Based Inventory Outputs

- Detected ice-cream packs from camera images
- Estimated inventory count
- Inventory trend over time

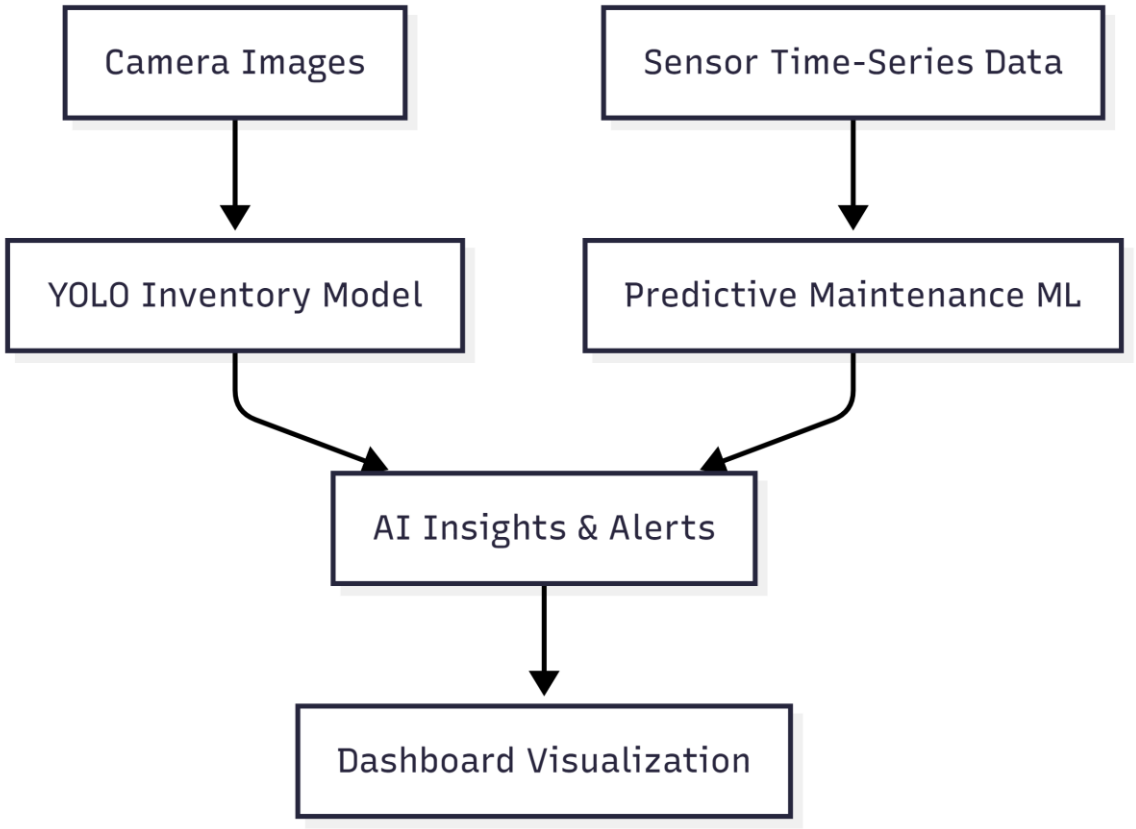
These outputs are displayed on the dashboard and also used as inputs for load estimation and control optimization.

Predictive Maintenance Outputs

Machine learning models analyse long-term sensor patterns to generate:

- Anomaly detection flags
- Abnormal vibration or power alerts
- System health indicators

These outputs help identify potential faults before failure occurs, improving system reliability.



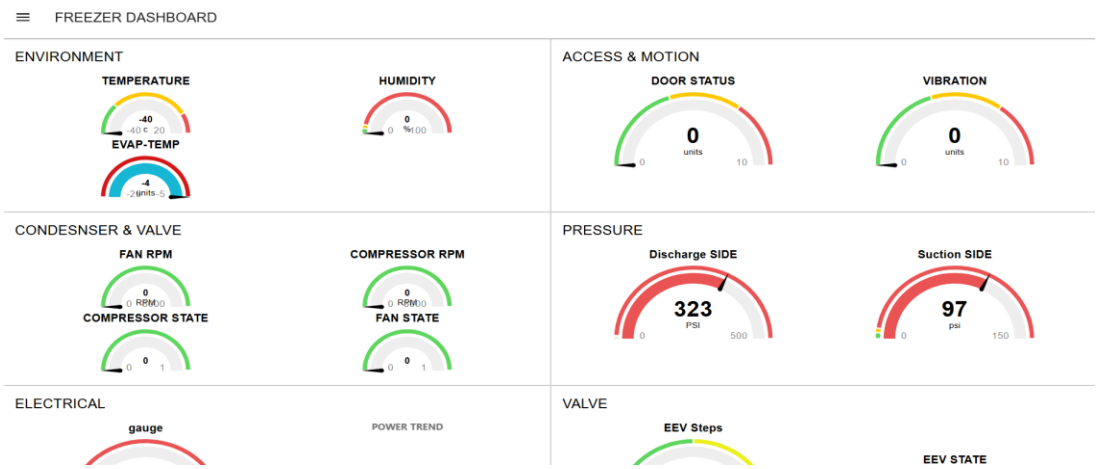
Output Mapping and Validation Tables

This section presents a structured mapping between hardware-level outputs, dashboard visualization, and AI/ML-generated insights, validating the end-to-end functionality of the proposed system.

Sensor Outputs and Dashboard Representation

Sensor / Module	**Measured Parameter**	**Unit**	**Dashboard Display Type**	**Purpose**
DS18B20 (Cabinet)	Cabinet Temperature	°C	Gauge + Line Chart	Monitor cooling effectiveness
DS18B20 (Evaporator)	Evaporator Temperature	°C	Line Chart	Heat absorption analysis
DHT22	Humidity	%RH	Gauge	Moisture monitoring
Reed Switch	Door Status	ON / OFF	Indicator	Detect heat ingress
INA219	Current	A	Numeric + Graph	Power monitoring

Sensor / Module	Measured Parameter	Unit	Dashboard Display Type	Purpose
INA219	Power	W	Line Chart	Compressor load estimation
SW-420	Vibration Level	Relative	Bar / Alert Flag	Mechanical fault detection
Pressure Sensors	High / Low Pressure	bar	Line Chart	Refrigeration cycle health
Line Temp Sensors	Suction / Discharge Temp	°C	Line Chart	Superheat & safety analysis

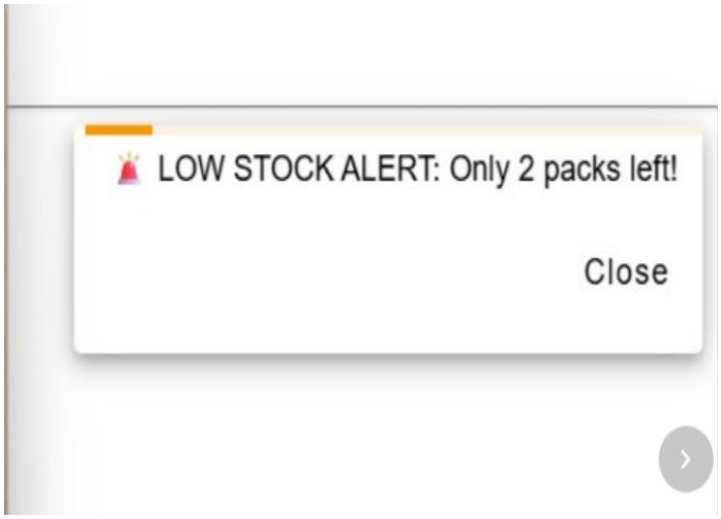


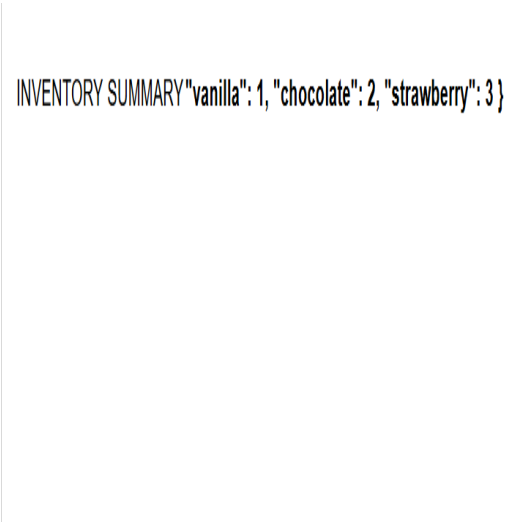
Control and Actuator Outputs → Dashboard Visualization

Actuator	Control Output	Unit	Dashboard Display	Control Objective
Compressor	Speed	RPM	Gauge / Numeric	Load-aware cooling
EEV	Step Position	Steps / %	Numeric Indicator	Superheat regulation
Condenser Fan	Speed	PWM (%)	Gauge	Heat rejection
Safety Relay	Status	ON / OFF	Status Indicator	Fault protection

Hardware & Control Outputs → AI / ML Inputs

Source	Data Used	Used By	Purpose
ESP32-CAM	Freezer Images	YOLO Model	Inventory detection
Vibration Sensor	Vibration Trend	ML Model	Fault detection
INA219	Power Pattern	ML Model	Abnormal load detection
Temperature Sensors	Temp Trends	ML Model	Predictive maintenance
Door Sensor	Door Frequency	Load Estimation	Load inference

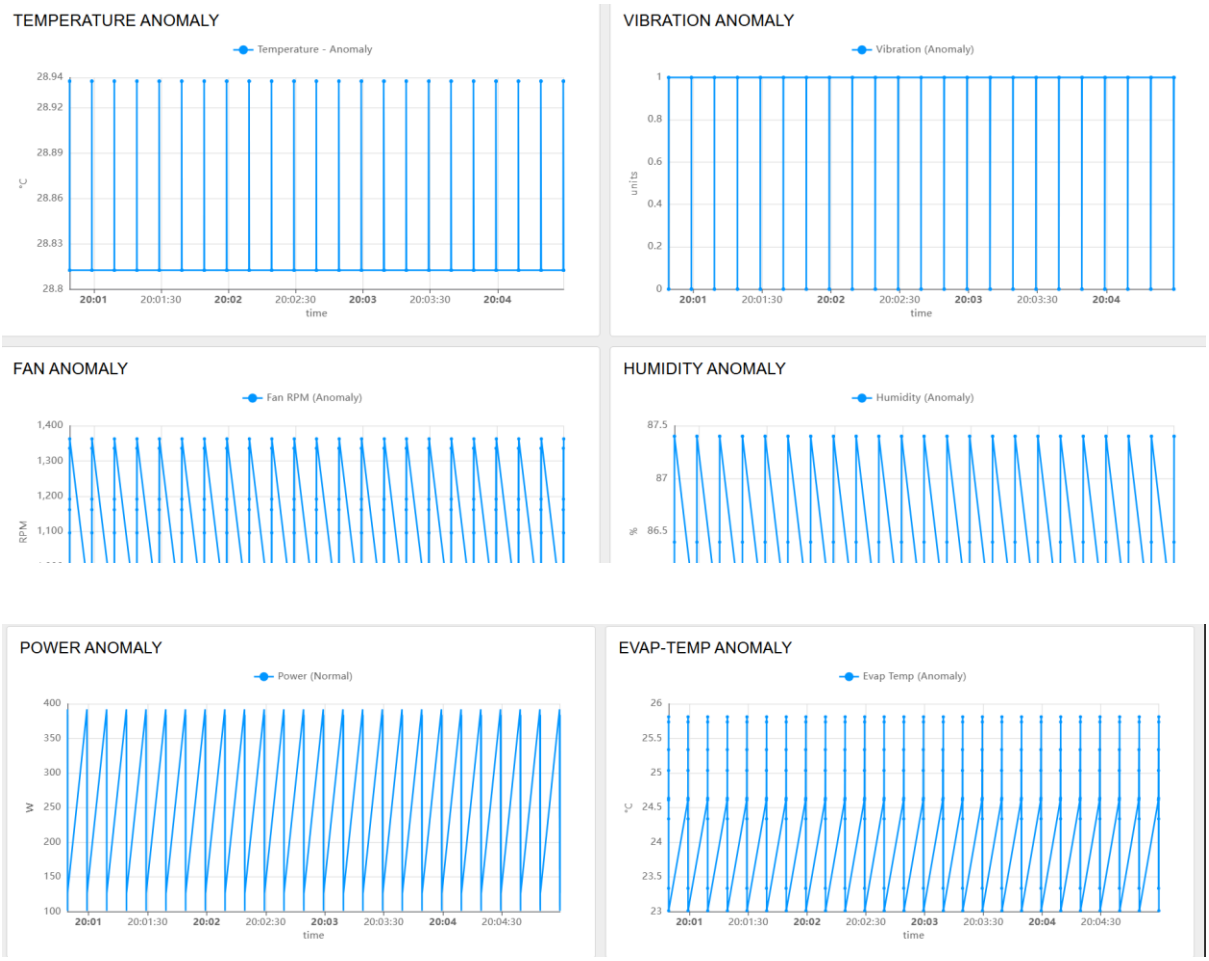




AI / ML Outputs → Dashboard Visualization

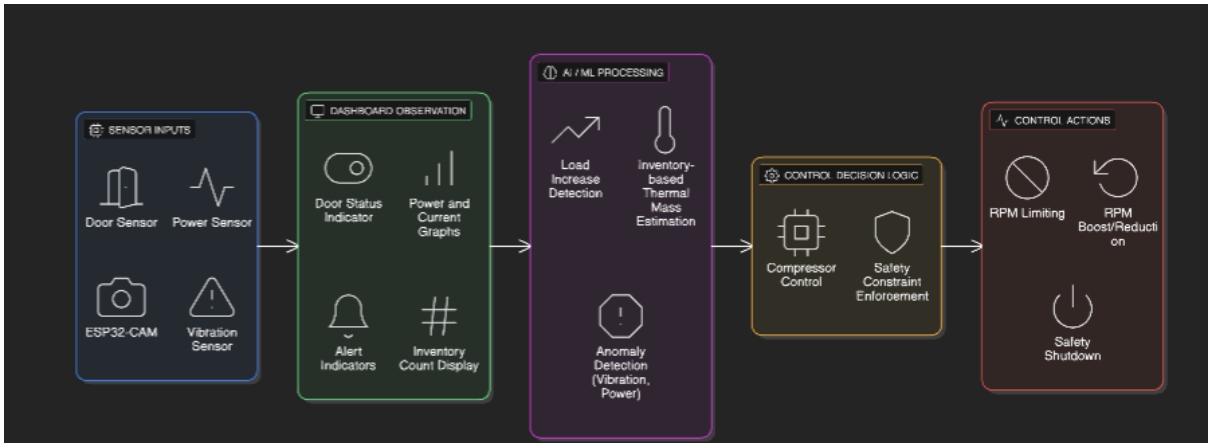
AI and ML Outputs Displayed on Dashboard

AI Module	Output Generated	Dashboard Representation	System Impact
YOLO Inventory Model	Inventory Count	Numeric Card	Load estimation
YOLO Inventory Model	Inventory Trend	Line Chart	Stock monitoring
Predictive Maintenance ML	Anomaly Flag	Warning Indicator	Fault awareness
Predictive Maintenance ML	Health Status	Status Card	Preventive action
Optimization Logic	Control Recommendation	Log / Indicator	Efficiency improvement



End-to-End Output Traceability (Sensor → AI → Control)

Sensor Input	**Dashboard Observation**	**AI Output**	**Control Action**
Door Open Event	Door Status ON	Load Increase Detected	Compressor RPM Boost
High Power Draw	Power Spike Graph	Anomaly Flag	RPM Limited
New Inventory Image	Increased Count	Higher Thermal Mass	Gradual RPM Increase
Excessive Vibration	Alert Indicator	Fault Detected	Safety Shutdown
Low Inventory	Reduced Load	Low Load Index	RPM Reduction



Conclusion

The system outputs obtained from the proposed smart freezer validate the successful integration of hardware sensing, adaptive control, cloud visualization, and AI-driven analytics. Real-time sensor data such as temperature, power, door status, and vibration are accurately captured at the edge and displayed on the dashboard, enabling continuous monitoring of freezer operation. Machine learning outputs, including inventory estimation and anomaly detection, provide higher-level insights that enhance system intelligence beyond conventional control. These AI outputs are directly linked to control decisions, such as compressor speed modulation and safety shutdowns, ensuring traceability from sensing to actuation. Overall, the observed outputs demonstrate a reliable closed-loop system capable of adaptive, efficient, and safe operation under varying load and operating conditions.