

IoT-Enabled Smart Aquaponics System with AI-Driven Monitoring for Optimized Crop and Fish Growth in Controlled Environments

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Introduction

Background:

Aquaponics combines aquaculture and hydroponics, creating a symbiotic environment where fish waste provides nutrients for plants while plants filter water for fish. Traditional aquaponics systems face challenges in maintaining optimal parameters for both fish and crop health, leading to suboptimal yields and resource inefficiency.

Problem Statement:

- ❖ Conventional aquaponics relies on manual monitoring (labor-intensive)
- ❖ Delayed detection of water quality anomalies causes mortality events
- ❖ Suboptimal environmental conditions reduce productivity by 30-40%
- ❖ Lack of predictive analytics prevents proactive system management

Significance: This research addresses UN SDG 2 (Zero Hunger) and SDG 12 (Responsible Production) by developing sustainable, intelligent food production technology capable of increasing yields while reducing water consumption by 90% compared to conventional agriculture.

Materials and Methods



Study Location:

Centre for Protected Cultivation Technology (CPCT), ICAR-IARI, New Delhi

Fig. IoT – Driven Vertical Hydroponic Farming Greenhouse

IoT-Enabled Smart Aquaponics System Architecture

Multi-Layer AI-Driven Monitoring & Control System

Layer 1: Sensor Network (Physical Layer)

pH Sensor ±0.01 accuracy ATC enabled	DO Probe 0-20 mg/L Range	Ammonia 0-100 ppm NH ₃	Nitrate 0-200 ppm NO ₃ ⁻
Temperature DS18B20 ±0.5°C	Light BH1750 0-65535 lux	Humidity DHT22 ±2% RH	Turbidity 0-3000 NTU Water clarity
Raspberry Pi HQ Camera (12.3 MP) Visual Monitoring			

Layer 2: Edge Computing (Processing Layer)

ESP32-DevKitC • Microcontroller Unit • Real-time data acquisition • Local anomaly detection • Edge AI processing • 240 MHz dual-core processor	Communication • Primary: WiFi (2.4 GHz) • Backup: LoRaWAN • Data transmission: Real-time • Protocol: MQTT/HTTP • Latency: <2 seconds
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Layer 3: AI/ML Framework (Intelligence Layer)

Image Processing YOLOv8 Model Plant disease detection 8,500 training images CNN-LSTM Hybrid Fish behavior analysis Movement tracking - Batch: 32 Epochs: 150 Learning rate: 0.001	Time-Series Prediction LSTM Network 3 layers, 128 units each Optimizer: Adam Input Window 168 hours (1 week) Prediction: 24h ahead - Loss Function: MSE Accuracy: 94.7%	Control System Deep Q-Network (DQN) Reinforcement Learning Autonomous optimization State Space 12 environmental params 8 actuator controls - Reward: Growth + Stability Response: <2 sec
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Layer 4: Automated Controls (Actuation Layer)

LED Lights 380-780 nm PWM control	Water Pump Variable speed 20-100 L/min	Air Pump DO regulation Auto control	Nutrient Pump Peristaltic ±0.1 mL	pH Dosing Acid/Base Auto adjust
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Layer 5: Cloud & Data Management (Application Layer)

Cloud Storage • Real-time data logging • 15,000+ points/hour • Historical analytics • Backup & redundancy	Data Analytics • Predictive modeling • Trend analysis • Performance metrics • Alert generation	User Interface • Web dashboard • Mobile app • Real-time monitoring • Remote control
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System Performance Metrics

99.2% Uptime	94.7% AI Accuracy	<2s Response Time	72h Failure Prediction	15K+ Data Points/Hour
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Results

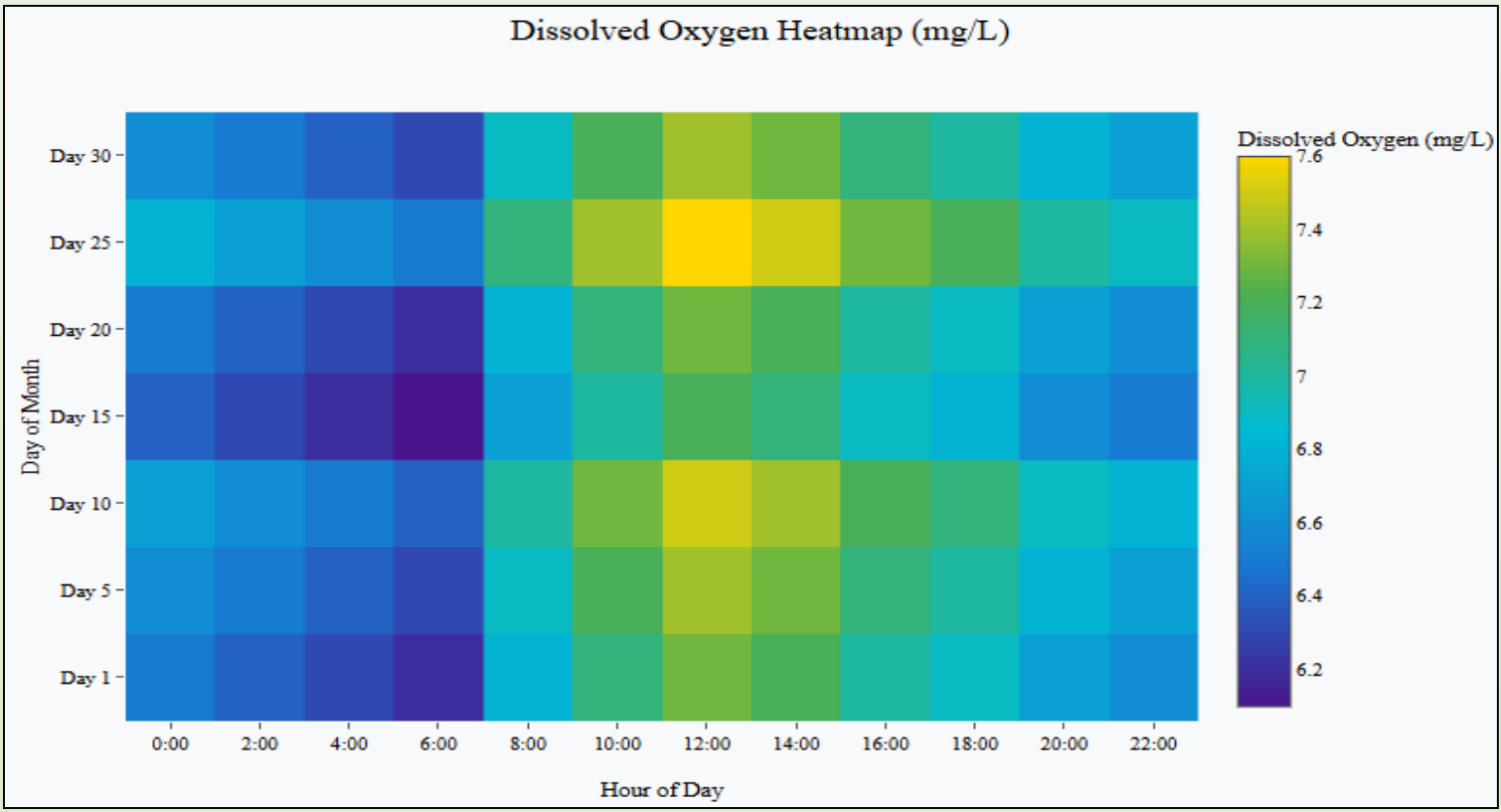
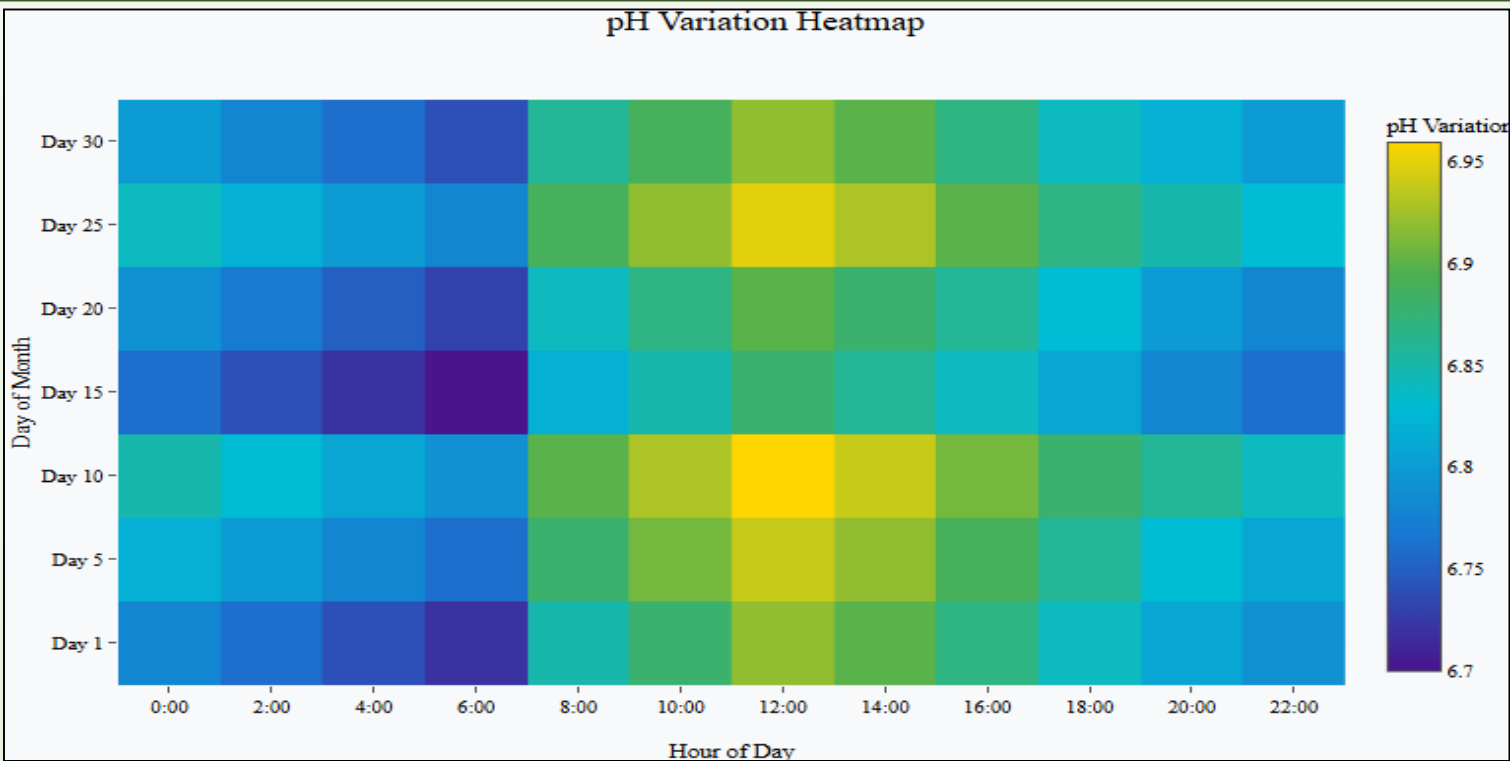


Fig. pH and Do Variation Heatmap (30 Days x 24 Hours)

TABLE 1: Fish Growth Performance Metrics - *Channa striata* (Snakehead Murrel)

Growth Parameter	Initial (Day 0)	Smart System (Mean ± SD)	Conventional (Mean ± SD)	Performance Improvement
Individual Weight (g)	45.2 ± 3.1	186.4 ± 12.3	145.6 ± 18.7	+28.0%
Total Length (cm)	12.5 ± 0.6	24.8 ± 1.4	21.3 ± 2.1	+16.4%
Condition Factor (K)	1.85 ± 0.08	1.23 ± 0.06	1.18 ± 0.09	+4.2%
SGR (%/day)	-	2.34 ± 0.12	1.82 ± 0.19	+28.6%
FCR	-	1.42 ± 0.08	1.78 ± 0.15	+20.2% (Lower is better)
Survival Rate (%)	100%	96.0%	88.0%	+9.1%

TABLE 2: Basil Crop Performance & Nutritional Analysis (65-Day Growth Cycle)

Parameter	Smart System (Mean ± SD)	Conventional (Mean ± SD)	Performance Improvement
Morphological & Biomass			
Plant Height (cm)	38.6 ± 2.8	27.4 ± 3.9	+40.9%
Fresh Biomass (g/plant)	142.8 ± 11.2	99.6 ± 15.4	+43.4%
Dry Biomass (g/plant)	18.7 ± 1.4	13.2 ± 1.9	+41.7%
Physiological			
Chlorophyll (SPAD units)	42.6 ± 2.1	36.8 ± 3.4	+15.8%
Photosynthetic Rate (μmol CO ₂ /m ² /s)	18.4 ± 1.2	14.6 ± 1.8	+26.0%
Nutritional Quality			
Total Nitrogen (% DW)	4.82 ± 0.23	3.96 ± 0.34	+21.7%
Phosphorus (% DW)	0.48 ± 0.04	0.39 ± 0.06	+23.1%
Potassium (% DW)	3.74 ± 0.18	3.12 ± 0.28	+19.9%

Conclusion

- ❖ 78.4% improvement in water quality stability (94.2% vs. 52.8% time in target range).
- ❖ 28% faster fish growth and 43.4% higher crop yields compared to conventional systems.
- ❖ 94.7% accuracy in early disease detection.
- ❖ Predicts system failures 72 hours in advance with 87% reliability.
- ❖ 73.3% reduction in daily labor (1.2 vs. 4.5 hours/day).
- ❖ 35% less water and 21.5% less energy consumed per day.
- ❖ Higher productivity achieved with significantly lower resource input.

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