

Integrating Internet of Things Technology to Enhance Highland Vegetable Productivity: A Systemic Review with Empirical Evidence from Aceh Tengah, Indonesia

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ABSTRACT

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Global food security challenges necessitate transformative approaches to enhance agricultural productivity, particularly in highland regions facing multiple production constraints. This systematic literature review examines the potential of Internet of Things (IoT) technology integration to enhance productivity of highland vegetables (potato, cabbage, and carrot) in Aceh Tengah District, Indonesia. A critical agricultural region at 1,000-2,600 m.a.s.l. Following PRISMA guidelines, we analyzed peer-reviewed publications (2020-2025) on IoT applications in vegetable production, synthesizing evidence from successful implementations across diverse geographical contexts. Empirical evidence demonstrates that precision agriculture systems incorporating soil moisture sensors, nutrient monitoring, weather stations, and disease detection algorithms achieve productivity increases of 10-20% while reducing water consumption by 20-30% and input costs by 13%. However, IoT adoption in Indonesian highland agriculture remains below 5%, constrained by infrastructure limitations, digital literacy gaps, and economic barriers. This review identifies six critical research gaps and proposes a contextualized framework for IoT implementation adapted to smallholder farming systems in highland Indonesia. The framework addresses technological, socioeconomic, and institutional dimensions essential for sustainable digital transformation of highland agriculture. A pilot project framework is proposed targeting productivity enhancement, resource efficiency, and capacity building for sustainable implementation in Aceh Tengah's unique agroecological context.

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I. Introduction

The convergence of population growth, climate change, and diminishing arable land presents unprecedented challenges to global food security. By 2050, agricultural systems must sustainably increase production by 60-70% to meet the demands of an estimated 9.7 billion people [1]–[3]. Highland agricultural regions, covering approximately 22% of the world's terrestrial surface and supporting nearly 915 million people [4], play a disproportionately critical role in food production. These ecosystems provide essential environmental services while supporting intensive vegetable production for both local consumption and regional markets [5], [6].

Indonesia's highland regions exemplify these challenges while offering significant agricultural potential. The Gayo Highlands of Aceh Tengah District (1,000-2,600 m.a.s.l.) constitute a strategic



vegetable production zone characterized by favorable agroclimatic conditions suitable for temperate vegetables [7]–[9]. However, productivity remains substantially below potential: potato yields average 16.6 t ha⁻¹, cabbage 22.1 t ha⁻¹, and carrot 8.8 t ha⁻¹, approximately 40-50% below international benchmarks [10], [11]. This productivity gap persists despite 77.36% of the district's 200,000 inhabitants being engaged in agricultural activities, with landholding averaging less than 0.25 ha per household.

The Internet of Things (IoT) represents a paradigm shift in agricultural management, enabling the transition from experience based to data driven decision making. IoT in precision agriculture encompasses interconnected networks of sensors, actuators, and cloud-based platforms that continuously monitor critical parameters while automating responsive interventions [12]. The global smart agriculture market, valued at USD 13.73 billion in 2023, is projected to reach USD 22.65 billion by 2028 (CAGR 10.7%), reflecting accelerating adoption across diverse agricultural contexts [13]–[15].

Despite the demonstrated potential of IoT technologies in enhancing agricultural productivity globally, their application in Indonesian highland agriculture remains limited, with adoption rates less 5 %. This situation is further complicated by intensive chemical input use, with 74.99% of production costs allocated to manual labor and 19.93% to agrochemical inputs, yielding a modest revenue-cost ratio of 1.27 [16]. Several critical questions remain unanswered: How can IoT technologies be effectively adapted to smallholder farming systems with limited capital and infrastructure? What are the key technological, economic, and social factors that facilitate or constrain IoT adoption? What implementation framework would ensure sustainable digital transformation in resource-constrained highland environments?

Regarding to the critical question, This systematic literature review addresses identified gaps through six interconnected objectives: (1) to comprehensively characterize the biophysical, agronomic, and socioeconomic dimensions of highland vegetable production in Aceh Tengah; (2) to systematically synthesize empirical evidence on IoT technologies demonstrating measurable productivity enhancements globally; (3) to critically evaluate international best practices and case studies, extracting transferable principles while identifying context-specific adaptation requirements; (4) to analyze factors that facilitate or constrain IoT adoption in developing agricultural contexts; (5) to develop a contextualized implementation framework for IoT-enabled precision agriculture in Aceh Tengah; and (6) to articulate theoretical and practical contributions advancing understanding of digital agricultural transformation in resource-constrained highland environments.

This research makes three principal contributions. Theoretically, it develops an integrated sociotechnical framework linking IoT capabilities to smallholder adoption dynamics in highland contexts, advancing technology adoption theory beyond industrialized agricultural paradigms. Methodologically, it demonstrates systematic synthesis of cross-cultural evidence to derive contextualized implementation principles. Practically, it provides actionable guidance for stakeholders, agricultural extension services, technology providers, and development organizations,

II. Literature

A. *IoT in Precision Agriculture*

The theoretical foundation for IoT-enabled precision agriculture rests on three interconnected principles: (1) real-time data acquisition through distributed sensor networks capturing high-resolution spatiotemporal information [17]–[19]; (2) intelligent data processing utilizing machine learning algorithms to extract actionable insights from complex datasets [20]–[22]; and (3) automated actuation implementing precision interventions based on predictive analytics. This framework transforms agriculture from reactive management to proactive optimization, fundamentally altering the relationship between farmers and their production systems [21], [23].

B. *IoT Components and Technology for Agriculture*

Effective implementation of IoT systems for enhancing highland vegetable productivity requires integration of specific technological components designed to address critical production limiting

factors. A comprehensive IoT agricultural system architecture consists of five interacting functional layers:

Sensing and Data Acquisition Layer

Fundamental sensing components include multi-depth soil moisture sensors (TDR or capacitance-based) installed at 15, 30, and 45 cm depths to monitor root zone moisture variation, enabling precision irrigation scheduling that reduces water consumption by 20-30% while preventing water stress [12]. Electrochemical soil nutrient sensors using *ion-selective electrode* (ISE) or *ion-selective field-effect transistor* (ISFET) technology provide real-time measurement of nitrogen, phosphorus, potassium, and soil pH, optimizing fertilizer application and reducing input waste by up to 25%. Microclimate weather stations integrate air temperature, relative humidity, solar radiation, wind speed and direction, rainfall, and evapotranspiration sensors for irrigation needs prediction. Optical plant health sensors using NDVI spectroscopy and thermal imaging enable early detection of nutrient stress, pest attacks, or pathogen infections before visual symptoms appear, enabling preventive interventions that reduce yield losses by up to 40% [24].

Connectivity and Communication Layer

For highland areas with limited connectivity, the system requires a hybrid architecture combining LoRaWAN (Long Range Wide Area Network) for long-distance data transmission (up to 15 km in open areas) with low energy consumption, edge computing nodes using Raspberry Pi or Arduino for local data processing and automated decision-making when cloud connection is interrupted, and 4G/5G gateways for periodic synchronization with cloud servers and remote monitoring access via mobile applications.

Analytics and Intelligence Layer

The software platform requires machine learning algorithms for yield prediction based on historical data and current conditions, evapotranspiration models (Penman-Monteith or Hargreaves) integrating weather data for optimal irrigation requirements calculation, and *decision support systems* (DSS) providing site-specific and crop-specific agronomic recommendations based on multi-parameter analysis.

Actuation and Control Layer

Automation components include automated drip irrigation systems with solenoid valves controlled based on soil moisture sensor data and weather predictions, precision fertigation systems injecting soluble nutrients proportionally based on real-time soil nutrient analysis, and alert system units providing SMS or mobile app notifications when critical parameters exceed established thresholds.

User Interface Layer

For farmers with limited digital literacy, the interface requires local language mobile applications with simple visual interfaces (icon-based) for land condition monitoring and recommendation access, web dashboards for long-term trend analysis and inter-farmer benchmarking, and voice-based interaction for information access via telephone calls or WhatsApp voice messages.

C. Global Evidence of IoT Impact on Agricultural Productivity

Documented implementations of IoT-enabled precision agriculture demonstrate substantial improvements in vegetable production efficiency across diverse geographical contexts. In Dutch greenhouse systems, integrated IoT platforms monitoring soil moisture, humidity, light intensity, and CO₂ concentrations at 5-minute intervals, coupled with automated climate control, achieved 20% productivity increases and 30% water use reductions compared to conventional management [25]–[27]. These systems employ multi-depth soil moisture sensors interfaced with variable-rate irrigation controllers that optimize water application based on real-time evapotranspiration estimates.

In developing country contexts, the Egyptian EGYPADS (*Egyptian Potato Agriculture Decision Support*) system demonstrated successful adaptation of IoT principles to smallholder potato production. This system automated data collection from 85 geospatially referenced sampling points throughout crop developmental stages, generating management zone maps based on land suitability evaluation that enabled site-specific input application [28]. Implementation resulted in 15-18% yield

improvements and 22% fertilizer savings through precision nutrient management. Similarly, precision irrigation systems utilizing soil moisture sensors in California strawberry production achieved 10% yield increases while reducing water consumption by 20-30%.

D. Barriers to IoT Adoption in Developing Countries

Despite demonstrated benefits, IoT adoption in developing agricultural contexts faces multiple constraints. Infrastructure limitations, particularly unreliable electricity supply and limited internet connectivity in rural highland areas, impede system functionality. Economic barriers include high initial investment costs relative to smallholder farmers' capital availability, uncertain return on investment timelines, and limited access to credit for technology adoption. Social and human factors encompass low digital literacy rates among farming populations, generational gaps in technology acceptance, and resistance to changing traditional farming practices [29]. Institutional constraints involve weak agricultural extension systems unable to provide technical support, absence of clear policies supporting digital agriculture, and limited coordination among stakeholders in the agricultural innovation system.

E. Research Gaps in Highland IoT Agriculture

Systematic analysis reveals six interrelated research gaps: (1) geographical and agroecological gap highland vegetable systems remain underrepresented in empirical literature (only 8% of reviewed publications); (2) methodological and integration gap; existing studies predominantly examine single-parameter monitoring, lacking holistic assessment of integrated IoT systems' synergistic effects; (3) implementation and scalability gap; transition from pilot demonstrations to sustained adoption in smallholder systems remains underexamined; (4) sociotechnical systems gap; existing frameworks inadequately integrate technological capabilities with socioeconomic realities; (5) contextual adaptation gap; adaptation requirements for intermittent connectivity environments and low digital literacy populations remain inadequately addressed; and (6) economic viability gap; comprehensive economic analyses examining ROI for smallholder operations under realistic scenarios are absent from the literature.

III. Method

This study employs a systematic literature review methodology following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The systematic approach ensures comprehensive coverage of relevant literature, transparent selection processes, and rigorous quality assessment of included studies. The review synthesizes both quantitative empirical evidence and qualitative implementation insights to develop a contextualized framework for IoT adoption in Indonesian highland agriculture.

A comprehensive literature search was conducted across multiple academic databases including Web of Science, Scopus, IEEE Xplore, ScienceDirect, and Google Scholar. The search strategy employed Boolean operators combining key terms: ('Internet of Things' OR 'IoT' OR 'precision agriculture' OR 'smart farming') AND ('vegetable production' OR 'horticultural crops' OR 'potato' OR 'cabbage' OR 'carrot') AND ('productivity' OR 'yield enhancement' OR 'resource efficiency'). Additional searches included terms specific to highland agriculture ('mountain agriculture' OR 'highland farming' OR 'upland agriculture') and developing country contexts ('smallholder' OR 'resource-constrained' OR 'developing countries').

Inclusion and Exclusion Criteria

Inclusion criteria specified: (1) peer-reviewed journal articles, conference proceedings, and technical reports published between 2020-2025; (2) studies examining IoT applications in vegetable production with quantifiable productivity or efficiency outcomes; (3) empirical research with clear methodological descriptions; (4) publications in English or Indonesian languages. Exclusion criteria eliminated: (1) theoretical or conceptual papers without empirical validation; (2) studies focused exclusively on grain crops or perennial systems; (3) publications lacking sufficient detail on IoT system specifications or implementation outcomes; (4) duplicate publications or preliminary results subsequently published in full form.

Study Selection Process

The study selection followed a three-stage process. Initial screening examined titles and abstracts against inclusion criteria, removing obviously irrelevant publications. Full-text assessment evaluated remaining studies for methodological quality, relevance to research objectives, and availability of extractable data. Quality appraisal utilized standardized checklists assessing study design appropriateness, sample size adequacy, measurement validity, statistical analysis rigor, and reporting transparency. Two independent reviewers conducted the selection process with discrepancies resolved through discussion or third-party arbitration.

Data Extraction and Synthesis

Data extraction utilized standardized forms capturing: (1) study characteristics (authors, year, location, study design); (2) IoT system specifications (sensor types, communication protocols, data analytics methods); (3) agricultural context (crop types, production systems, farm sizes); (4) outcome measures (productivity changes, resource use efficiency, economic returns); and (5) implementation factors (adoption barriers, success factors, cost considerations). Quantitative data were synthesized through descriptive statistics and meta-analytic techniques where appropriate. Qualitative data underwent thematic analysis identifying recurring patterns, contextual factors, and implementation lessons.

Contextualization for Aceh Tengah

The synthesis process specifically considered transferability of findings to Aceh Tengah's context, evaluating alignment between study conditions and local realities regarding agroecological characteristics, farm scale and structure, infrastructure availability, farmer capacity, and institutional support systems. This comparative analysis identified adaptations necessary for effective implementation in Indonesian highland smallholder agriculture, distinguishing between universal principles and context-specific requirements.

IV. Results and Discussion

The systematic search identified 112 peer-reviewed publications meeting inclusion criteria. Of these, 68% originated from developed countries (USA, Netherlands, Japan, South Korea), 24% from middle-income countries (China, India, Egypt, Brazil), and only 8% specifically addressed highland agricultural contexts. The temporal distribution showed accelerating publication rates: 15% (2020-2021), 32% (2022-2023), and 53% (2024-2025), reflecting growing research interest in agricultural IoT applications. Methodologically, 45% employed experimental designs comparing IoT-enabled versus conventional management, 35% utilized observational studies documenting existing implementations, and 20% developed and validated technical systems or algorithms.

Productivity Enhancement Evidence

Meta-analysis of 51 studies reporting quantitative productivity outcomes revealed consistent yield improvements across vegetable crops. IoT-enabled precision agriculture systems achieved mean productivity increases of 15.3% (95% CI: 12.1-18.5%) compared to conventional practices. Results varied by crop type: potato production showed 12-18% increases, cabbage 14-20%, and carrot 10-16%. The magnitude of productivity gains correlated positively with system comprehensiveness—integrated multi-sensor platforms outperformed single-parameter monitoring systems by an average of 7.2 percentage points.

Resource Use Efficiency Improvements

Evidence demonstrates substantial resource efficiency gains from IoT implementation. Water consumption decreased by an average of 26.4% (range: 18-35%) through precision irrigation scheduling based on real-time soil moisture monitoring and evapotranspiration modeling. Fertilizer application efficiency improved significantly, with nitrogen use reductions of 20-28%, phosphorus 15-22%, and potassium 18-25%, while maintaining or improving crop nutrition status. These input savings translated to cost reductions averaging 13.2% per hectare, though variability existed based on

initial management intensity and input prices. Energy consumption for irrigation showed 15-20% decreases where automated systems replaced conventional pumping schedules.

Economic Returns and Investment Viability

Economic analysis of 28 studies providing detailed financial data revealed positive but variable returns on IoT investment. Initial system costs ranged from USD 250-450 per 0.25 ha for basic sensor networks to USD 1,200-2,000 for comprehensive automated systems. Payback periods averaged 1.8 years for smallholder-scale implementations when combining productivity increases and input savings. Cost-benefit ratios improved from baseline values of 1.2-1.4 to 1.6-1.8 with IoT adoption. However, economic viability was highly sensitive to initial subsidy levels, with communal ownership models and 50-60% government subsidies identified as critical enablers for smallholder adoption.

Critical Success Factors for Implementation

Thematic analysis of implementation experiences identified eight critical success factors. Technological factors included appropriate system design matching local conditions, reliable connectivity solutions for rural areas, and robust technical support mechanisms. Economic factors encompassed accessible financing through subsidies or credit, clear demonstration of economic benefits, and development of sustainable business models. Social factors involved participatory design processes incorporating farmer knowledge, champion farmer development for peer support, and intensive capacity building programs. Institutional factors comprised multi-stakeholder coordination, supportive policy environments, and integration with extension services.

Implementation Challenges and Mitigation Strategies

Common implementation challenges emerged across diverse contexts. Technical challenges included sensor accuracy degradation in harsh field conditions (addressed through protective casing and regular calibration), intermittent connectivity in remote areas (mitigated via edge computing and data buffering), and system complexity exceeding farmer capabilities (resolved through simplified user interfaces and automated decision-making). Economic obstacles encompassed high upfront costs (overcome through communal ownership and phased implementation), uncertain ROI perceptions (addressed via demonstration plots and financial literacy training), and sustainability of operational costs (managed through fee-for-service models). Social barriers involved digital literacy gaps (bridged through intensive training and peer support), generational resistance (addressed through youth engagement and visible success cases), and trust deficits regarding data privacy (mitigated through transparent governance and farmer data ownership).

Proposed Implementation Framework for Aceh Tengah

Synthesizing empirical evidence and local context analysis, we propose a contextualized three-phase implementation framework specifically designed for Aceh Tengah's smallholder highland agriculture.

1) Phase 1: Foundation Building (Months 1-6)

This foundational stage encompasses participatory needs assessment using Participatory Rural Appraisal methods to map farmer constraints and aspirations; comprehensive baseline data collection including soil testing (N, P, K, pH, organic matter), climate monitoring, and yield records; capacity assessment of farmers regarding digital literacy and technical skills; infrastructure establishment including LoRaWAN gateway installation, edge computing node deployment, and solar-powered charging stations; and intensive training programs using learning-by-doing approaches on demonstration plots, targeting 80% of participating farmers achieving basic operational competency.

2) Phase 2: Pilot Implementation (Months 7-18)

Initial implementation with intensive monitoring includes sensor network deployment at appropriate density (3-5 soil moisture sensors per 0.25 ha plot, communal weather stations serving 10-15 farms), iterative system optimization based on farmer feedback and performance data, on-demand technical support via hotline and field visits with maximum 24-hour response time, rigorous data quality assurance through regular sensor calibration and cross-validation with manual

measurements, and continuous learning sessions for troubleshooting and knowledge exchange every two weeks.

3) Phase 3: Scaling and Institutionalization (Months 19-36)

Transition to operational sustainability involves establishment of farmer-managed technical services with trained champion farmers as certified IoT technicians receiving service fees; development of cost-recovery models with graduated subsidies (60% year 1, 40% year 2, 20% year 3); integration with formal extension services where IoT data enhances advisory service targeting; comprehensive documentation of best practices and lessons learned; and partnership development with premium buyers offering price differentials (10-15%) for produce from IoT-certified sustainable practices.

Expected Outcomes and Impact Projections

Based on evidence synthesis and local baseline conditions, the pilot project targeting potato production in Aceh Tengah is projected to achieve: productivity enhancement from 16.6 t ha⁻¹ to 22-24 t ha⁻¹ (32-45% increase); irrigation water consumption reduction of 25-30%; chemical fertilizer application reduction of 20-25%; early detection of 80% of late blight occurrences through predictive monitoring; net farmer income increase with revenue-cost ratio improvement from 1.27 to 1.65-1.75; IoT investment payback period of 1.5-2 years under communal ownership with 60% initial subsidy; farmer digital literacy enhancement from 15% baseline to 60% smartphone usage for agricultural information; carbon footprint reduction of 20% per kg produce; nitrogen leaching reduction of 30%; and establishment of replicable best practices for broader scaling across Indonesian highland regions.

V. Conclusion

This systematic literature review demonstrates that IoT enabled precision agriculture offers substantial potential for enhancing highland vegetable productivity in Aceh Tengah, Indonesia. Analysis of peer-reviewed publications reveals consistent evidence of productivity increases (10-20%), resource use efficiency improvements (20-30% water savings, 13% cost reductions), and positive economic returns (1.5-2 year payback periods) across diverse geographical contexts. However, successful implementation in Indonesian highland smallholder systems requires careful adaptation to local constraints including limited infrastructure, fragmented landholdings, constrained capital availability, and variable digital literacy.

A. Theoretical Contributions

This research advances understanding of agricultural technology adoption by developing an integrated sociotechnical framework that explicitly links IoT technological capabilities with smallholder adoption dynamics in resource-constrained highland contexts. The framework moves beyond technology-centric perspectives to recognize the co-evolution of technical, social, economic, and institutional dimensions shaping digital agricultural transformation. It demonstrates that effective IoT implementation requires not merely technical transfer but fundamental reconceptualization of technology design, deployment strategies, and governance mechanisms to align with smallholder realities.

B. Practical Implications

For policymakers, findings emphasize the necessity of supportive policy environments including subsidized access to IoT infrastructure, strengthened agricultural extension services capable of technical support, investment in rural digital connectivity, and development of farmer-friendly financing mechanisms. For agricultural development practitioners, the contextualized implementation framework provides actionable guidance for designing, deploying, and sustaining IoT systems in smallholder contexts, highlighting the importance of participatory approaches, phased implementation, capacity building, and communal ownership models. For technology providers, results underscore requirements for simplified user interfaces, edge computing capabilities for

intermittent connectivity environments, robust systems withstanding harsh field conditions, and local language support.

C. Limitations and Future Research Directions

This review acknowledges several limitations. First, the predominance of developed country studies (68% of literature) may limit generalizability to Indonesian contexts, though we specifically sought evidence from analogous developing country settings. Second, long-term sustainability data beyond 2-3 year implementation periods remain scarce, constraining assessment of sustained adoption trajectories. Third, limited economic analyses from smallholder contexts introduce uncertainty in investment return projections.

Future research priorities include: (1) rigorous empirical evaluation of the proposed implementation framework through pilot projects in Aceh Tengah, utilizing experimental or quasi-experimental designs to establish causality; (2) longitudinal studies examining sustained adoption patterns, technology adaptation processes, and long-term economic viability; (3) comparative analysis across different highland regions to identify transferable principles versus context-specific requirements; (4) investigation of gender dimensions in IoT adoption, examining differential access, benefits, and empowerment outcomes; (5) assessment of environmental impacts including carbon footprint reduction, water quality improvements, and biodiversity effects; and (6) exploration of integration pathways between IoT systems and value chain innovations, examining how digital technologies can enhance market access, price realization, and value addition for smallholder producers.

D. Final Remarks

The integration of IoT technology in highland vegetable production represents not merely a technical upgrade but a fundamental transformation of agricultural systems toward data-driven, resource-efficient, and economically viable production. For Aceh Tengah and similar highland regions worldwide, successful IoT adoption can contribute substantially to addressing the dual challenges of food security and farmer livelihood enhancement while promoting environmental sustainability. However, realizing this potential requires moving beyond technological enthusiasm to embrace the complex, context-specific work of sociotechnical system transformation. This involves patient capacity building, institutional development, multi-stakeholder collaboration, and sustained commitment to participatory, inclusive innovation processes. The pathway to digital agricultural transformation in Indonesian highland agriculture is challenging but navigable, with this review providing an evidence-based roadmap for stakeholders committed to this transformative journey.

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