International Journal of Advanced Agriculture and Research

ISSN: 3121-6420

Volume 2, Issue 2 | April, 2026
(An Academians Publishers of Research & Academic Resources)

OPEN ACCESS

Review Article

Received: 12-03-2026 Accepted: 18-04-2026 Published: 29-04-2026

A Review Paper: Synergizing IoT-Enabled Urban Vertical Agriculture and Drought-Tolerant Crops for Sustainable Food Systems in the Era of Climate Change and Industry 4.0

Raza Sabri
Department of Agriculture.

Abstract: This review paper synthesizes two emerging paradigms in sustainable agriculture: Internet of Things (IoT)-enabled urban vertical agriculture and drought-tolerant pearl millet (Pennisetum glaucum) cultivation, particularly the innovative RHB 273 hybrid. Drawing from recent conceptual and empirical research, this paper examines how technological innovation in controlled-environment agriculture and genetic advances in arid-land crops can collectively address the intersecting challenges of food security, climate change, youth disengagement from agriculture, and the demands of Industry 4.0. The review analyzes the ESP32 microcontroller-based IoT systems for vertical hydroponic agriculture as proposed for Malaysian contexts and compares these with the physiological and genetic drought-adaptation mechanisms of pearl millet developed for semi-arid tropics. Key findings suggest that while urban vertical agriculture offers high-density, technology-driven solutions for metropolitan areas, pearl millet provides a low-input, climate-resilient option for marginal rural lands. The paper proposes an integrated framework combining these approaches within Technical and Vocational Education and Training (TVET) curricula to foster intergenerational learning, community engagement, and sustainable food systems. Policy recommendations include standardization of vertical hydroponic systems, enhanced marketing channels for community gardens, and expanded cultivation of biofortified drought-tolerant varieties across climate-vulnerable regions.

Keywords: *Internet of Things (IoT), urban vertical agriculture, pearl millet, drought tolerance, RHB 273, TVET, food security, Industry 4.0, climate resilience*

1. Introduction

The convergence of climate change, population growth, urbanization, and technological revolution presents unprecedented challenges and opportunities for global agricultural systems. According to the Food and Agriculture Organization (FAO, 2023), agricultural productivity must increase by approximately 60% by 2050 to meet projected food demand, yet this must be accomplished under conditions of increasing water scarcity, rising temperatures, and declining arable land per capita. Two distinct but potentially complementary responses have emerged from recent research: technology-intensive urban vertical agriculture enabled by the Internet of Things (IoT), and genetically improved drought-tolerant crops adapted to marginal environments.

The first paradigm, exemplified by the conceptual framework proposed for Malaysia by Ayub et al. (2025), leverages IoT-enabled vertical hydroponic systems to transform urban spaces into productive agricultural zones. This approach addresses the declining interest in agriculture among Generation Z and Generation Alpha by repositioning farming as a high-tech, sustainable, and socially responsible career pathway. Using ESP32 microcontrollers equipped with soil moisture, temperature, and humidity sensors, these systems optimize resource efficiency while providing hands-on learning opportunities integrated into Technical and Vocational Education and Training (TVET) curricula.

The second paradigm, represented by the development of RHB 273—the world's first three-way drought-tolerant hybrid pearl millet—offers a solution for arid and semi-arid regions where conventional crops fail (Jain et al., 2026). Developed through collaboration between Shri Karan Narendra Agriculture University (SKNAU), the Rajasthan Agriculture Research Institute (RARI), and the International Crops Research Institute for the Semi-Arid

Tropics (ICRISAT), this variety achieves 13-28% higher grain yields and 10-15% higher stover yields than existing hybrids while maturing within 75-76 days and demonstrating resistance to Downy Mildew, Blast, and Smut.

This review paper aims to: (1) critically analyze the technological and pedagogical frameworks of IoT-enabled urban vertical agriculture; (2) examine the physiological, genetic, and agronomic characteristics of drought-tolerant pearl millet with emphasis on RHB 273; (3) identify synergies and trade-offs between these approaches; and (4) propose an integrated framework for sustainable agricultural development that addresses both urban and rural contexts within the broader agenda of Industry 4.0 and climate adaptation.

2. Methodology

This review synthesizes peer-reviewed literature, technical reports, and policy documents published between 2014 and 2026. Sources include the conceptual paper by Ayub et al. (2025) on IoT-enabled TVET and urban vertical agriculture in Malaysia, and the research paper by Jain et al. (2026) on pearl millet and RHB 273 development. Additional sources include government policy documents (Mimos, 2015; Miti, 2018), technical specifications from agricultural technology providers (Cultivatedearth, 2025; Lyinegroup, 2025), and supporting literature on agricultural education (Zaremohzzabieh et al., 2022), community gardens (Ahmad et al., 2024), and pearl millet genomics (Varshney et al., 2017).

The review employs a comparative thematic analysis, organizing findings around five principal themes: (1) technological infrastructure for sustainable agriculture; (2) physiological and genetic mechanisms of drought adaptation; (3) educational and intergenerational learning frameworks; (4) socioeconomic and nutritional impacts; and (5) policy and implementation challenges. The integration of these themes informs the proposed complementary framework presented in Section 8.

3. IoT-Enabled Urban Vertical Agriculture: Technological Infrastructure and Educational Integration

3.1 The ESP32 Microcontroller and Sensor Systems

The foundation of the proposed urban vertical agriculture system rests upon the ESP32 microcontroller, a development platform that integrates Wi-Fi and Bluetooth functionalities for IoT applications. As documented by Ayub et al. (2025), the ESP32 originated from the Maker community's recognition in 2014 of the ESP-01 module, a US$5 Wi-Fi solution compatible with the Arduino platform (Benchoff, 2014; Cording, 2022). The NodeMCU ESP32 has since evolved into a widely utilized platform for prototyping and implementing interconnected agricultural devices.

Within vertical hydroponic systems (VHS), the ESP32 supports three primary sensor applications. First, soil moisture sensors ascertain water content within growing media, enabling effective oversight and management of water resources. Second, temperature and humidity sensors monitor environmental conditions conducive to plant development. Third, integrated data from these sensors provides insights into evaporative demands, allowing users to modify irrigation schedules appropriately. Yusoff et al. (2023) demonstrated that maintaining optimal humidity levels through IoT-enabled monitoring prevents both overwatering and underwatering, optimizes water consumption, and mitigates plant stress.

3.2 Vertical Hydroponic Systems: Productivity Metrics

The productivity advantages of vertical hydroponic systems over conventional agriculture are substantial. According to Cultivatedearth (2025), traditional soil-based agriculture yields approximately 10 to 20 heads of lettuce per square meter, while flat hydroponic systems increase yields to 30 to 40 heads per square meter. Vertical agriculture, by stacking crop layers, achieves densities ranging from 50 to 100 heads per square meter per "floor." The minimum yield ratio established by Ayub et al. (2025) is Traditional : Flat hydroponic : Vertical hydroponic = 10 : 30 : 50.

In the Malaysian context, urban rooftop spaces encompass approximately 13.3 square kilometers across public, commercial, and industrial buildings. Subject to structural suitability (flat rooftops), this area could be repurposed for urban vertical agriculture, provided that farmers determine urban farming as more economically advantageous than alternative uses such as solar farm installation (Ayub et al., 2025).

3.3 Case Study: Commercial Vertical Hydroponic Containers in Mauritius

A regional agribusiness in Mauritius implemented vertical hydroponic containers to maximize yield within limited spatial footprints while ensuring optimal resource utilization (Lyinegroup, 2025). Given the climatic similarity between Mauritius and Malaysia, Ayub et al. (2025) argue that the successful implementation of this container system establishes a foundational framework for advancing urban vertical agriculture projects in Malaysia. The containerized approach offers scalability and reproducibility, addressing the need for standardized systems that can be deployed across diverse urban environments.

3.4 Integration with TVET Curricula and Intergenerational Learning

A distinctive contribution of the conceptual framework proposed by Ayub et al. (2025) is the alignment of standardized vertical hydroponic technologies with TVET curricula. This integration serves multiple objectives:

equipping graduates with technical competencies in IoT programming, sensor calibration, and data analytics; creating a pipeline of trainers who can transfer knowledge to younger generations; and fostering intergenerational learning through hands-on activities involving parents and children.

Specifically, TVET graduates trained in ESP32 programming can subsequently instruct preschool, elementary, and secondary school students—particularly those belonging to Generation Z and Generation Alpha—in agricultural technology applications. This strategy cultivates early engagement with agricultural technology while addressing the documented disinterest of younger demographics in conventional farming. As Zaremohzzabieh et al. (2022) observed, Generation Z and Generation Alpha perceive traditional agriculture as involving manual labor, lacking technological advancement, and carrying unfavorable associations, rendering agriculture a profession of last resort. By reframing agriculture as a high-tech, IoT-enabled enterprise, urban vertical agriculture potentially reverses this perception.

4. Drought-Tolerant Pearl Millet: Physiological and Genetic Foundations

4.1 Global Significance and Production Context

Pearl millet (Pennisetum glaucum) ranks as the sixth most important cereal crop globally and serves as the primary staple food for over 90 million people in Sub-Saharan Africa and South Asia (Jain et al., 2026). India is the world's largest producer, accounting for approximately 40% of global production, with cultivation concentrated in the arid and semi-arid regions of Rajasthan, Haryana, Gujarat, Maharashtra, and Uttar Pradesh. Rajasthan alone contributes roughly 45% of India's pearl millet area, reflecting the crop's dominance in desert and semi-desert farming systems.

The crop is believed to have originated in West Africa approximately 4,000-5,000 years ago, spreading across Sub-Saharan Africa and into Asia. Today, pearl millet is cultivated across 25-30 million hectares worldwide, spanning the Sahel region of Africa (Nigeria, Niger, Senegal, Mali) and South Asia (India, Pakistan, Bangladesh).

4.2 Physiological Mechanisms of Drought Adaptation

Jain et al. (2026) identify four principal physiological mechanisms enabling pearl millet's survival and productivity under water-scarce conditions.

Deep and Efficient Root Systems: Pearl millet develops extensive root systems that access soil moisture from lower horizons even when surface layers are desiccated. The root architecture exhibits high root-to-shoot ratios under drought conditions, prioritizing water uptake over aboveground biomass accumulation. Root hairs increase surface area for water absorption.

Stomatal Regulation and Transpiration Efficiency: As a C4 plant, pearl millet possesses a photosynthetic pathway that concentrates carbon dioxide in bundle sheath cells, reducing the frequency of stomatal opening required for photosynthesis. This mechanism dramatically improves water use efficiency compared to C3 crops such as wheat and rice.

Osmotic Adjustment: When subjected to water stress, pearl millet maintains cellular integrity through the accumulation of compatible solutes (osmolytes) that stabilize proteins and maintain turgor pressure. This osmotic adjustment enables continued cellular function even under low water potential conditions.

Rapid Crop Cycle (Drought Escape): Many pearl millet varieties, including RHB 273, mature within 75-76 days, enabling the crop to complete its life cycle during brief monsoon seasons or with limited irrigation. This strategy, termed 'drought escape,' allows flowering and grain set before the onset of severe drought.

4.3 Agronomic Advantages for Marginal Environments

Beyond drought tolerance, pearl millet offers agronomic advantages specifically suited to marginal environments. It grows on sandy, low-fertility, and acidic soils where other cereals cannot establish. Its efficient nitrogen use enables acceptable yields without heavy fertilizer inputs, reducing cost burdens on smallholder farmers. The short growing season (60-90 days for most varieties) allows integration into multiple cropping systems, including as a catch crop or relay crop following monsoon-dependent primary crop failures. Critically, pearl millet stover remains nutritious long after grain harvest, providing invaluable livestock fodder during lean dry seasons and creating additional income streams for farming households (Yadav & Bidinger, 2008).

5. RHB 273: A Landmark Three-Way Drought-Tolerant Hybrid

5.1 Development History and Institutional Collaboration

The development of RHB 273 represents the culmination of collaborative research between SKNAU Jobner (through its unit RARI Durgapura) and ICRISAT Hyderabad, in coordination with the ICAR-AICRP (Pearl Millet) Project Coordinating Unit. As documented by Jain et al. (2026), the collaboration has been described by RARI Director Dr. Harphool Singh as a milestone achievement for dry and hyper-arid regions receiving less than 400 mm of annual rainfall.

The Indian central government formally notified RHB 273 via Gazette Notification No. S.O. 6123(E) dated December 31, 2025, making it available for cultivation in the dry regions of Rajasthan, Haryana, and Gujarat. On January 4, 2026, Union Agriculture and Farmers Welfare Minister Shri Shivraj Singh Chouhan released 184 improved crop varieties, among which RHB 273 was prominently included.

5.2 Scientific Innovation: The Three-Way Hybrid Approach

What distinguishes RHB 273 from conventional hybrids is its status as the world's first three-way drought-tolerant hybrid pearl millet. Traditional hybrids (single crosses) utilize two genetically distinct parent lines, whereas three-way hybrids employ three genetically diverse parents, conferring greater heterosis (hybrid vigor) and a broader genetic base for stress tolerance (Jain et al., 2026).

RHB 273 was developed using a CMS (Cytoplasmic Male Sterility)-based female parent RMS 30A, derived from the cross ICMA 97111 × ICMB 13666, and the restorer line RIB 3135-18. Using Bonjh F1 as the male parent, this three-way hybrid system offers cost-effective seed production while enhancing field identification and reducing bird damage. Developed under the scientific direction of Dr. S. K. Jain, the variety addresses the twin challenges of productivity and resilience in North-Western India's arid zones.

5.3 Yield Performance and Disease Resistance

RHB 273 is a dual-purpose variety providing both grain and stover in quantities exceeding existing hybrids. Key yield parameters include average grain yield of 22-25 quintals per hectare and stover yield of 48-50 quintals per hectare. Compared to popular commercial hybrids, this represents a 13-28% improvement in grain yield and a 10-15% improvement in fodder production (Jain et al., 2026).

The variety demonstrates high resistance to three major fungal diseases: Downy Mildew (caused by Sclerospora graminicola), Blast, and Smut. This disease resistance reduces fungicide requirements, lowers production costs, and ensures more stable yields under disease-pressure conditions.

5.4 Nutritional Profile and Hidden Hunger Mitigation

Pearl millet is an extraordinarily nutrient-dense cereal. RHB 273 contains 44 ppm iron and 37 ppm zinc, compared to significantly lower levels in polished rice (Jain et al., 2026). Protein content is approximately 10.5%—substantially higher than rice and comparable to wheat. These micronutrient levels are particularly relevant to 'hidden hunger,' a form of malnutrition affecting over 2 billion people globally, characterized by sufficient caloric intake but deficiency in essential vitamins and minerals.

Vice Chancellor Professor Dr. Pushpendra Singh Chauhan of SKNAU Jobner highlighted that regular pearl millet consumption improves health outcomes, reduces medical expenditure by decreasing the burden of anemia, iron deficiency, and zinc-related developmental disorders, and provides a cost-effective dietary solution for vulnerable populations (cited in Jain et al., 2026). Pearl millet's high dietary fiber content supports digestive health and has been associated with reduced risk of type 2 diabetes, cardiovascular disease, and obesity. Its naturally gluten-free composition expands its consumer base to individuals with celiac disease or gluten intolerance.

6. Comparative Analysis: Urban Vertical Agriculture vs. Drought-Tolerant Pearl Millet

6.1 Technological Intensity and Input Requirements

Urban vertical agriculture, as conceptualized by Ayub et al. (2025), is a high-technology, high-input system requiring substantial initial capital expenditure for IoT sensors, microcontrollers, hydroponic infrastructure, and climate control systems. Operational costs include electricity for pumps, lighting, and data transmission, as well as regular maintenance of electronic components. The authors acknowledge elevated initial expenditures, data security vulnerabilities, and substantial energy consumption as key challenges associated with IoT implementation in vertical agriculture.

Conversely, drought-tolerant pearl millet represents a low-technology, low-input system suitable for resource-constrained rural environments. RHB 273 requires no specialized infrastructure beyond conventional farming equipment, relies on natural rainfall (or minimal supplemental irrigation), and demands no electronic monitoring systems. Seed costs are the primary recurring expense, with minimal fertilizer requirements due to the crop's efficient nitrogen use.

6.2 Spatial Context and Land Use Efficiency

Urban vertical agriculture excels in spatial efficiency, achieving yields of 50-100 heads of lettuce per square meter per layer, making it ideal for land-scarce urban environments. The repurposing of rooftop spaces (13.3 square kilometers available in Malaysia) transforms non-productive urban surfaces into productive agricultural zones without competing with housing, transportation, or commercial land uses.

Pearl millet, by contrast, requires extensive land area—approximately 25-30 million hectares globally—and is suited to rural or peri-urban settings where land is available but water is scarce. Its spatial efficiency is measured not in yield per square meter but in yield per unit of water consumed, an equally critical metric in arid environments.

6.3 Water Use Efficiency

Both systems demonstrate superior water use efficiency compared to conventional agriculture, but through different mechanisms. Vertical hydroponic systems recycle nutrient solutions, reducing water consumption by up to 90% compared to soil-based irrigation (Ayub et al., 2025). IoT-enabled monitoring optimizes irrigation scheduling based on real-time evaporative demand, preventing both overwatering and underwatering.

Pearl millet achieves water efficiency through physiological adaptation: C4 photosynthesis reduces transpiration losses, deep rooting captures soil moisture from lower horizons, osmotic adjustment maintains cellular function under low water potential, and rapid maturation enables drought escape. Varshney et al. (2017) documented that pearl millet can produce grain with as little as 300-400 mm of seasonal rainfall, a threshold below which maize and sorghum fail.

6.4 Nutritional and Socioeconomic Contexts

Urban vertical agriculture typically produces leafy greens (lettuce, herbs, microgreens) with high water content and moderate nutritional density per unit mass. The primary socioeconomic value lies in local food production, reduced transportation distances, community engagement, and educational applications rather than caloric or micronutrient provision.

Pearl millet, particularly RHB 273 with 44 ppm iron and 37 ppm zinc, provides substantial caloric density (approximately 350 kcal per 100g), high-quality protein, and critical micronutrients for vulnerable populations. Its socioeconomic value includes food security for smallholder farmers, income from grain and stover sales, livestock feed, and nutritional supplementation for anaemia prevention.

6.5 Youth Engagement and Educational Potential

Urban vertical agriculture offers superior potential for engaging Generation Z and Generation Alpha due to its alignment with technology, automation, data analytics, and urban lifestyles. The integration of ESP32 programming into TVET curricula positions agriculture as a digital career pathway rather than manual drudgery. Intergenerational learning occurs through hands-on activities where children and parents jointly operate IoT-enabled systems.

Pearl millet cultivation, while offering fewer direct technology engagement opportunities, provides educational value in plant physiology, drought adaptation mechanisms, genetics, and climate resilience. However, for urban youth who have never experienced water scarcity or food production, pearl millet may appear remote and irrelevant compared to IoT-enabled hydroponics.

7. Structural Challenges and Limitations

7.1 Marketing Channel Constraints for Community Gardens

Ayub et al. (2025) identify marketing channel constraints as a critical impediment to urban vertical agriculture sustainability. Drawing from Ahmad et al. (2024), the authors report that 62% of Community Garden produce is sold directly to consumers, while intermediaries (wholesalers and distributors) display minimal interest in procuring goods from community-based gardens. This direct-to-consumer model limits market reach, creates price volatility, and constrains scalability. The recommendation proposed by Ayub et al. (2025) is local governmental intervention to advocate for Community Gardens and foster connections with local, state, and national distribution networks. Without institutional support for market access, urban vertical agriculture risks remaining a niche activity rather than achieving the scalability necessary for meaningful food system transformation.

7.2 Standardization Deficits in Vertical Hydroponic Systems

A second challenge identified by Ayub et al. (2025) is the absence of standardization in vertical hydroponic systems. Diverse system designs, sensor configurations, software platforms, and data protocols impede interoperability, complicate maintenance, increase training requirements, and reduce the scalability of solutions. Standardization would facilitate alignment of TVET curricula, enable economies of scale in component manufacturing, simplify technical support, and accelerate adoption.

The proposed solution involves implementing standardized vertical hydroponic containers in conjunction with IoT-enabled ESP32 systems, establishing a universal platform that enhances inclusivity through dialogue and cooperation within and among communities.

7.3 Stigma, Shelf Life, and Market Linkages for Pearl Millet

Jain et al. (2026) identify three constraints limiting wider pearl millet adoption. First, pearl millet remains stigmatized as a 'poor man's food' in parts of South Asia, leading to its displacement by rice and wheat as incomes rise, even among populations for whom it would be nutritionally superior. Addressing this cultural barrier requires consumer awareness campaigns and development of appealing processed food products.

Second, post-harvest storage presents challenges due to pearl millet's lipid content, which can undergo rancidity, reducing shelf life compared to wheat or rice. Developing low-cost storage technologies suitable for village-level use is an important research priority.

Third, market linkages and price support mechanisms for pearl millet are weaker than for major cereals, discouraging commercial cultivation in accessible areas where farmers have viable alternatives.

7.4 Climate Change Projections and Agricultural Transitions

Climate change is projected to increase average temperatures, reduce and redistribute rainfall in arid and semi-arid regions, and increase the frequency and intensity of droughts (Boote et al., 2011). These changes threaten productivity of water-intensive crops (wheat, rice, maize) while expanding the ecological niche where pearl millet can outperform competitors. Models consistently show pearl millet maintaining or increasing its relative advantage as global temperatures rise, with heat tolerance up to 42°C.

For urban vertical agriculture, climate change presents both opportunities and risks. Increased temperatures and weather volatility may increase demand for controlled-environment agriculture that insulates production from external conditions. Conversely, energy costs for cooling and pumping may rise, and water scarcity may affect even efficient hydroponic systems if municipal water supplies are constrained.

8. An Integrated Framework for Sustainable Agricultural Development

This review proposes an integrated framework recognizing that urban vertical agriculture and drought-tolerant pearl millet address different but complementary segments of the food system, rather than competing solutions.

For urban and peri-urban contexts: IoT-enabled vertical hydroponic systems are most appropriate for high-density metropolitan areas where land is scarce, youth populations are concentrated, technology infrastructure is available, and markets for fresh produce exist. Integration with TVET curricula positions these systems as educational platforms for digital agriculture skills, potentially reversing youth disengagement from farming. Priority investments should include standardized container systems, ESP32 sensor networks, and formal linkages between community gardens and distribution networks.

For rural arid and semi-arid contexts: Drought-tolerant pearl millet, particularly RHB 273, is most appropriate for smallholder farming systems in regions receiving less than 400 mm annual rainfall, where soil fertility is low, and where conventional crops fail. The variety's 13-28% yield advantage, disease resistance, and biofortification for iron and zinc address food security, income generation, and nutritional deficiencies simultaneously. Priority investments should include seed multiplication and distribution systems, farmer training on agronomic practices, storage technology development, and market linkages.

For educational and intergenerational applications: Both systems offer pedagogical value, but through different mechanisms. Urban vertical agriculture provides hands-on IoT programming, sensor calibration, and data analytics within TVET curricula. Pearl millet provides instruction in plant physiology, drought adaptation, genetics, and climate-resilient farming systems. Ideally, agricultural education curricula should include both modules, enabling students to understand the full spectrum from high-tech urban solutions to low-tech rural adaptations.

Synergistic pathways: Potential synergies between the two systems include: (1) IoT environmental monitoring technologies developed for vertical agriculture could be adapted for pearl millet field trials, enabling precision agriculture applications; (2) biofortification lessons from RHB 273 (44 ppm iron) could inform nutrient management in hydroponic systems; (3) TVET graduates trained on ESP32 systems could apply programming skills to agricultural sensor networks in both contexts; (4) standardized vertical hydroponic containers could serve as demonstration units at agricultural extension centers alongside pearl millet demonstration plots.

9. Policy Recommendations

Based on the synthesized evidence, the following policy recommendations are proposed:

For urban vertical agriculture:

Local governments should establish formal linkages between community gardens and regional distribution networks to address the marketing channel constraint whereby 62% of produce is sold directly to consumers (Ahmad et al., 2024; Ayub et al., 2025).

Standardized vertical hydroponic container specifications should be developed to enable economies of scale, simplified maintenance, and aligned TVET curricula.

Incentives (tax rebates, reduced utility rates, technical assistance) should be provided for building owners converting suitable flat rooftops to vertical agriculture, noting the 13.3 square kilometers of available rooftop space in Malaysia.

For drought-tolerant pearl millet:

Seed multiplication and distribution systems for RHB 273 should be expanded across Rajasthan, Haryana, and Gujarat, targeting regions receiving less than 400 mm annual rainfall.

Consumer awareness campaigns should address the 'poor man's food' stigma through marketing emphasizing nutritional benefits (44 ppm iron, 37 ppm zinc) and climate resilience.

Low-cost, village-level storage technologies should be developed to extend pearl millet shelf life and reduce post-harvest losses.

Minimum support prices for pearl millet should be maintained or enhanced to encourage commercial cultivation.

For agricultural education:

TVET curricula should include modules on both IoT-enabled vertical agriculture and climate-resilient crop varieties, ensuring graduates understand the full spectrum of sustainable agriculture technologies.

Intergenerational learning programs should be established where TVET graduates (Generation Z) instruct younger students (Generation Alpha) in

ESP32 programming and vertical system operation.

10. Future Research Directions

Several knowledge gaps warrant future investigation:

First, empirical validation of the proposed conceptual framework is needed. The Ayub et al. (2025) paper is explicitly conceptual, proposing a model that requires testing through pilot implementations of standardized vertical hydroponic containers with IoT-enabled ESP32 systems in Malaysian urban settings.

Second, comparative water use efficiency studies under controlled conditions would quantify the relative advantages of vertical hydroponics versus pearl millet across different climate scenarios and water availability regimes.

Third, longitudinal studies tracking TVET graduates trained on IoT agricultural systems would assess employment outcomes, skill retention, and knowledge transfer to younger generations.

Fourth, research on consumer acceptance and willingness-to-pay for vertically produced produce versus pearl millet-based products would inform marketing strategies.

Fifth, genomic studies building on the Varshney et al. (2017) pearl millet genome sequence could identify additional loci associated with heat tolerance, water use efficiency, and nutrient density, enabling further genetic improvement beyond RHB 273.

Sixth, climate modeling studies should project the relative productivity of vertical agriculture versus pearl millet under various climate scenarios (IPCC RCP 4.5, 6.0, 8.5) to inform long-term agricultural planning.

11. Conclusion

This review has synthesized two emerging paradigms in sustainable agriculture: IoT-enabled urban vertical agriculture and drought-tolerant pearl millet cultivation. The conceptual framework proposed by Ayub et al. (2025) demonstrates how ESP32 microcontroller systems can transform urban spaces into productive agricultural zones while engaging Generation Z and Generation Alpha through TVET-integrated curricula. Standardized vertical hydroponic containers, as successfully implemented in Mauritius, offer a scalable model for Malaysia's 13.3 square kilometers of available rooftop space, achieving productivity ratios of 10:30:50 for traditional, flat hydroponic, and vertical hydroponic systems respectively.

Simultaneously, the development of RHB 273—the world's first three-way drought-tolerant hybrid pearl millet—represents a landmark achievement in crop science. With 13-28% higher grain yield, 10-15% higher stover yield, resistance to Downy Mildew, Blast, and Smut, and biofortification for iron (44 ppm) and zinc (37 ppm), this variety addresses food security, income generation, and hidden hunger across arid and semi-arid regions receiving less than 400 mm annual rainfall.

Rather than competing paradigms, these approaches address complementary segments of the food system. Urban vertical agriculture offers high-density, technology-driven production suitable for metropolitan areas with land scarcity and youth populations open to digitally-enabled farming careers. Pearl millet offers low-input, climate-resilient production suitable for rural areas where water scarcity and soil poverty constrain conventional agriculture. Both contribute to food security, resource efficiency, and climate adaptation, but through different mechanisms and in different contexts.

As climate change progressively constrains the viability of water-intensive cereal production systems, and as urbanization concentrates populations in cities disconnected from food production, both technological and genetic innovations will be required to build resilient, sustainable, and equitable food systems for the coming decades.

References

Ahmad, A. A., Omar, N. R. N., Yusoff, M. M., & Ahmad, M. A. (2024). From Farm to Table concept: The profile and dynamics of urban farming on agrofood supply chain in Malaysia. *The FFTC Journal of Agricultural Policy*, 2, 17-34.

Ahmad, M. H., Razali, S. N., & Rosly, R. N. R. (2019). Integration of Augmented Reality Application for Interactive Internet of Things Module. *International e-Learning Carnival and Conference 2019*, 1-2.

Ayub, M. O., et al. (2025). Integrating IoT-enabled vertical agriculture with TVET for sustainable urban development and intergenerational learning in Malaysia. *International Journal of Business and Technology Management*, 7(6), 72.

Benchoff, B. (2014). *New Chip Alert: The ESP8266 WiFi Module (It's $5)*. Hackaday. https://hackaday.com/2014/08/26/new-chip-alert-the-esp8266-wifi-module-its-5/

Bidinger, F. R., Mahalakshmi, V., & Rao, G. D. P. (1987). Assessment of drought resistance in pearl millet. *Australian Journal of Agricultural Research*, 38(1), 37-48.

Boote, K. J., Ibrahim, A. M. H., Lafitte, R., McCulley, R., Woodfield, D., & Smith, C. W. (2011). Position statement on crop adaptation to climate change. *Crop Science*, 51(6), 2337-2343.

Cording, S. (2022). *What Is the ESP32?* Elektormagazine. https://www.elektormagazine.com/articles/what-is-the-esp32

Cultivatedearth. (2025). *How Many Lettuce Heads Can You Grow Per Square Meter?*

https://cultivatedearth.com/en/lettuce/lettuce-yield-per-square-meter/

Food and Agriculture Organization. (2023). *The State of Food and Agriculture: Climate change, agriculture and food security*. FAO.

Government of India. (2025). Gazette Notification No. S.O. 6123(E), dated December 31, 2025 — Notification of RHB 273 for cultivation in Rajasthan, Haryana and Gujarat. Ministry of Agriculture and Farmers Welfare.

ICRISAT. (2024). *Pearl Millet Research for Development in Semi-Arid Tropics*. ICRISAT Publication Series.

Islam, R. (2024). *Micro-Farming - The Next Big Leap in Urban Revitalization*. ResearchGate.

Jain, Y., Singh, K., Soni, V., Ikram, A., & Agrawal, R. (2026). Pearl Millet: Thriving in Arid Lands with Minimal Water: A Research Paper on Drought-Tolerant Agriculture and the Development of RHB 273. *SSRN Electronic Journal*.

Lazim, R. M., Nawi, N. M., Masroon, M. H., Abdullah, N., & Iskandar, M. C. M. (2020). Adoption of IR4.0 into agricultural sector in Malaysia: Potential and challenges. *Advances in Agricultural and Food Research Journal*, 1(2).

Lyinegroup. (2025). *Commercial vertical hydroponic containers*. https://www.lyinegroup.com

Mimos. (2015). *National Internet of Things (IoT) Strategic Roadmap - A Summary*. https://www.mimos.my/iot/National_IoT_Strategic_Roadmap_Summary.pdf

Ministry of International Trade and Industry (MITI). (2018). *National Policy on Industry 4.0*. https://www.miti.gov.my/miti/resources/National%20Policy%20on%20Industry%204.0/Industry4WRD_Final.pdf

RARI-ICRISAT Collaboration Report. (2025). Development and Characterisation of RHB 273: The World's First Three-Way Drought-Tolerant Hybrid Pearl Millet. Rajasthan Agriculture Research Institute.

Singh, P., & Virmani, S. M. (1996). Modelling growth and yield of chickpea under drought. *Field Crops Research*, 46(1-3), 41-59.

SKNAU Jobner Press Release. (2026, February). Development of World's First Three-Way Drought-Tolerant Pearl Millet Hybrid RHB 273. Shri Karan Narendra Agriculture University.

Varshney, R. K., Shi, C., Thudi, M., et al. (2017). Pearl millet genome sequence provides a resource to improve agronomic traits in arid environments. *Nature Biotechnology*, 35(10), 969-976.

Yadav, O. P., & Bidinger, F. R. (2008). Dual-purpose landraces of pearl millet (Pennisetum glaucum) as sources of high stover and grain yield for arid zone environments. *Plant Genetic Resources*, 6(1), 73-78.

Yusoff, M. S. M., Ismail, A., Yusoff, N., & Wahi, R. (2023). Agriculture: innovations in vertical cultivation systems for community development. *E3S Web of Conferences*, 437, 03007.

Zaremohzzabieh, Z., Krauss, S. E., D'Silva, J. L., Tiraieyari, N., Ismail, I. A., & Dahalan, D. (2022). Towards agriculture as career: Predicting students' participation in the agricultural sector using an extended model of the theory of planned behavior. *The Journal of Agricultural Education and Extension*, 28(1), 67-92.