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Reimagining Urban Agriculture: LED-Powered Underground Rice Farming for Smart Sustainable Cities

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Abstract

Rapid urbanization in metropolitan regions has intensified agricultural land conversion, particularly affecting rice-based food systems that remain highly land-dependent and less adaptable to conventional urban farming approaches. This study developed a conceptual and technical model of LED-powered underground rice farming as an alternative production system to address structural constraints on urban food security and sustainable agricultural development. A qualitative descriptive approach was employed, integrating secondary data analysis, comparative case studies, and content analysis to construct a system design encompassing spatial configuration, water management, and controlled lighting environments. The results indicated that the proposed system enabled precise regulation of microclimatic conditions, including light spectra, photoperiod, and water circulation, thereby supporting continuous production cycles and improving resource-use efficiency. The integration of recirculating irrigation and spectrum-adjusted LED lighting reduce water consumption and minimize dependency on chemical inputs while maintaining crop quality in enclosed environments. Furthermore, the model demonstrated strong spatial efficiency, making it applicable for high-density urban areas with limited arable land. However, implementation remained constrained by high initial investment costs and dependence on reliable energy infrastructure. These findings highlighted the strategic role of technological innovation, integrated system design, and multi-stakeholder collaboration in advancing resilient urban food systems. Overall, this study provided a scalable pathway for transforming rice cultivation toward sustainable and smart metropolitan agriculture.

1. Introduction

Rapid urbanization has intensified competition for land resources within metropolitan regions, exerting mounting pressure on agricultural production systems worldwide. This pressure is projected to intensify further, as global estimates indicate that at least 70% of the world's population will reside in urban areas by 2050, a demographic transition that is progressively displacing food production from urban and peri-urban landscapes [1]. The expansion of residential areas, industrial estates, transportation infrastructure, and commercial facilities has accelerated agricultural land conversion, thereby diminishing the availability of productive land for food production. This phenomenon is particularly pronounced in Indonesia, where rice constitutes not only the principal staple food but also a strategically vital commodity underpinning national food security. System dynamics modeling of Indonesia's land use trajectory further suggests that agricultural land, including paddy fields, is projected to experience escalating conversion pressure toward built up areas, with food vulnerability anticipated to intensify by 2045 particularly on Java Island, despite its standing as the nation's sole food surplus region [2]. This trajectory is already empirically evident according to the Central Bureau of Statistics (BPS), Indonesia's paddy harvested area declined from 10.21 million hectares in 2023 to approximately 10.05 million hectares in 2024, while rice production for food consumption decreased correspondingly from 31.10 million tons to 30.62 million tons over the same period [3]. These trends collectively underscore a structural challenge in sustaining rice production amid intensifying urban development pressures, thereby reinforcing the urgency of identifying alternative production paradigms capable of decoupling staple food cultivation from competition over scarce surface land.

This challenge extends beyond mere agricultural productivity, bearing direct implications for the resilience and directly affects the resilience of urban food systems. Although various forms of urban agriculture including hydroponics, aeroponics, rooftop farming, and vertical farming, have demonstrated considerable efficacy in producing horticultural commodities, their applicability to staple crops remains markedly constrained. A systematic scoping review of controlled environment agriculture (CEA) research corroborates this limitation, revealing that the field continues to be dominated by leafy greens and high value horticultural crops, with substantial gaps persisting in research addressing cereal staples that demand larger cultivation volumes, extended growth cycles, and more intricate environmental regulation [4]. Rice cultivation, in particular, necessitates specific environmental conditions, continuous water availability, and considerably larger production spaces relative to most commercially cultivated urban crops. Compounding this constraint, the expansion of conventional vertical farming frameworks to accommodate staple crops is severely circumscribed by urban spatial politics: above ground urban agricultural initiatives consistently encounter intense structural competition from high value real estate markets and housing developments, rendering surface level land access economically untenable for low margin grain production. Consequently, prevailing urban agriculture models have yet to furnish a scalable solution capable of sustaining rice production within highly urbanized metropolitan environments.

Recent advances in *Controlled Environment Agriculture* (CEA) have engendered novel opportunities to circumvent land constraints through the integration of environmental control technologies, automated irrigation systems, and artificial lighting. Among emerging innovations, underground farming has garnered increasing attention as an alternative production system that capitalizes on underutilized subterranean spaces such as basements, tunnels, metro stations, and other underground infrastructures for agricultural purposes. A recent feasibility analysis of urban underground farms identifies independence from prevailing weather conditions and the shortening of supply chains as principal benefits of this approach, while concurrently noting that elevated energy costs and the absence of comprehensive regulatory frameworks remain salient barriers warranting further attention [1]. By operating within tightly controlled environments, underground farming offers the potential to sustain year round production while substantially minimizing dependence on climatic variability and surface land availability. Subterranean environments inherently afford natural geothermal stability, which significantly attenuates external ambient temperature fluctuations and reduce the excessive HVAC (*Heating, Ventilation,* and *Air Conditioning*) cooling energy demanded required by above ground glasshouses, thereby furnishing a more thermally stable microclimate profile conducive to supporting energy intensive agricultural infrastructure.

The operational performance of underground farming systems is profoundly contingent upon advances in *Light Emitting Diode* (LED) technology. LED's afford superior energy efficiency, minimal thermal emission, extended operational lifespan, and the capacity to deliver crop specific light spectra conducive to optimizing photosynthetic processes. Recent optimization studies corroborate that supplementing white LED illumination with deep red and far red wavelengths at elevated photon flux densities can substantially augment biomass accumulation relative to single spectrum lighting regimes [6]. Nevertheless, the extant body of evidence has predominantly concentrated on vegetables and high value horticultural crops, whereas research integrating LED supported underground farming specially for rice cultivation remains conspicuously limited. This disparity stems, in part, from the fact that leafy greens require comparatively lower light intensities and more straightforward environmental parameters. Conversely, stabilizing cereal crop cultivation within zero sunlight subterranean spaces demands highly precise cyber physical architectures, encompassing automated instrumentation networks capable of continuously monitoring and dynamically adjusting specialized microclimatic factors alongside artificial radiation schedules. Furthermore, grain crops such as like rice exhibit pronoounced photoperiodic sensitivities that necessitate elevated *Photosynthetic Photon Flux Density* (PPFD) and dynamic spectral modulation transitioning, from vegetative blue red wavelengths toward reproductive stage configurations to ensure proper panicle initiation and grain filling processes in the absence of natural sunlight. Foundational investigations into rice cultivation within plant factories utilizing artificial lighting have demonstrated the feasibility of cultivating rice to maturity entirely under LED illumination [7]. While more recent protocols have further elucidated that calibrated adjustments to light intensity and photoperiod at specific development stages can abbreviate the rice growth cycle without compromising yield within fully enclosed plant factory systems [8]. Collectively, these findings affirm the biological feasibility of LED based rice cultivation nevertheless, such investigations remain largely confined to controlled experimental settings rather than being conceptually integrated within a holistic underground urban farming system. This gap assumes particular significance given the strategic centrality of rice to food security and sustainable urban development.

Accordingly, this study formulates a conceptual and technical framework that integrates an underground cultivation space, a recirculating irrigation systems, environmental control mechanisms, and spectrum adjusted LED lighting to facilitate rice production under fully controlled conditions. The novelty of this study resides in extending the application of underground farming beyond conventional horticultural production toward staple crop cultivation, thereby positioning it as a potential constituent of smart and sustainable urban food systems [1][4]. By coupling technological innovation with food security imperatives, this research contributes a novel conceptual perspective on enhancing urban food resilience and advancing sustainable metropolitan development.

2. Research Methods

2.1 Research Design

This study employed a qualitative descriptive approach to develop a conceptual and technical framework for LED-powered underground rice farming in metropolitan areas. The research was designed as a conceptual model development study, focusing on the integration of controlled environment agriculture, underground farming systems, and LED-based cultivation technologies to address challenges related to agricultural land scarcity, urban food security, and sustainable city development. A qualitative approach was considered appropriate because the study aimed to synthesize existing scientific knowledge, technological evidence, and practical experiences into an integrated framework rather than testing causal relationships through experimental procedures [9].

2.2 Data Sources and Collection

The study relied exclusively on secondary data obtained from multiple sources to ensure comprehensive coverage of the research topic. Data were collected from peer-reviewed scientific articles indexed in international databases, government publications, statistical reports, policy documents, and technical reports related to urban agriculture, food security, underground farming, controlled environment agriculture (CEA), and LED technology applications in crop production. In addition, comparative case studies from countries that have implemented underground farming systems, including Japan, the Netherlands, and the United

Kingdom, were reviewed to identify technological configurations, operational characteristics, and implementation challenges relevant to metropolitan environments. The data collection process was conducted through systematic document screening. Literature sources were selected based on their scientific relevance, publication quality, recency, and direct contribution to the development of underground agricultural systems and controlled cultivation technologies. Priority was given to publications addressing urban food systems, sustainable agriculture, resource-use efficiency, and technological innovation in agricultural production.

2.3 Data Validation and Analytical Procedures

Data validity was ensured through source triangulation by comparing information obtained from scientific literature, official statistical publications, policy documents, and documented case studies. This procedure was employed to minimize bias and improve the credibility of the findings. Reliability was strengthened by using consistent inclusion criteria during document selection and by cross-verifying technological and operational information reported across multiple sources. The collected data were analyzed using qualitative content analysis. The analysis focused on identifying key themes related to land-use efficiency, environmental control systems, irrigation management, LED lighting applications, crop production performance, resource utilization, and implementation constraints. Information extracted from the selected sources was systematically categorized and synthesized to generate a comprehensive understanding of the opportunities and challenges associated with underground rice farming in metropolitan regions.

2.4 Conceptual Framework Development

Based on the analytical results, an integrated conceptual framework was developed to support rice cultivation within underground environments. The framework consisted of four interrelated components like underground spatial configuration, recirculating irrigation systems, environmental control mechanisms, and spectrum-adjusted LED lighting systems. These components were designed to accommodate the physiological requirements of rice while optimizing land utilization, water efficiency, and production continuity under controlled conditions. The framework development process incorporated principles of controlled environment agriculture and sustainable urban food systems. Particular attention was given to the integration of resource-efficient technologies capable of supporting food production in densely populated metropolitan areas. The resulting framework served as the analytical basis for evaluating the potential contribution of LED-powered underground rice farming to urban food resilience and sustainable city development.

3. Result and Discussion

3.1 Structural Challenges of Rice Production in Metropolitan Areas

The analysis revealed that agricultural land conversion has become one of most significant constraints affecting rice production in metropolitan regions [13], [14]. Rapid urban expansion continuously reallocates productive agricultural land toward residential, industrial, transportation, and commercial purposes, reducing the spatial capacity available for food production. Unlike horticultural commodities that can be cultivated through compact urban farming systems, rice production remains highly dependent on adequate growing space and continuous water availability [19]. Consequently, urbanization generates a disproportionately greater impact on rice production than on most urban agricultural commodities.

The findings further indicated that existing urban agriculture models have primary focused on vegetables, herbs, and other high value crops. While these systems contribute to local food availability, their capacity to support staple food production remains limited. This finding is consistent with previous studies emphasizing that current urban agriculture technologies have not sufficiently addressed staple crop cultivation within densely populated cities. As a result [11], a technological gap persists between urban food demand and the capacity of metropolitan areas to produce strategic food commodities locally [20]. These findings highlight the urgency of developing alternative agricultural systems capable of operating independently from conventional land constraints while maintaining production efficiency. Such as systems are increasingly important for strengthening urban food resilience and supporting sustainable metropolitan development.

3.2 Development of the LED-Powered Underground Rice Farming Framework

The principal outcome of this study was the development of an integrated conceptual framework for underground rice cultivation supported by LED technology. The framework was designed around four interconnected subsystems, like underground cultivation space, recirculating irrigation, environmental control, and spectrum-adjusted LED lighting.

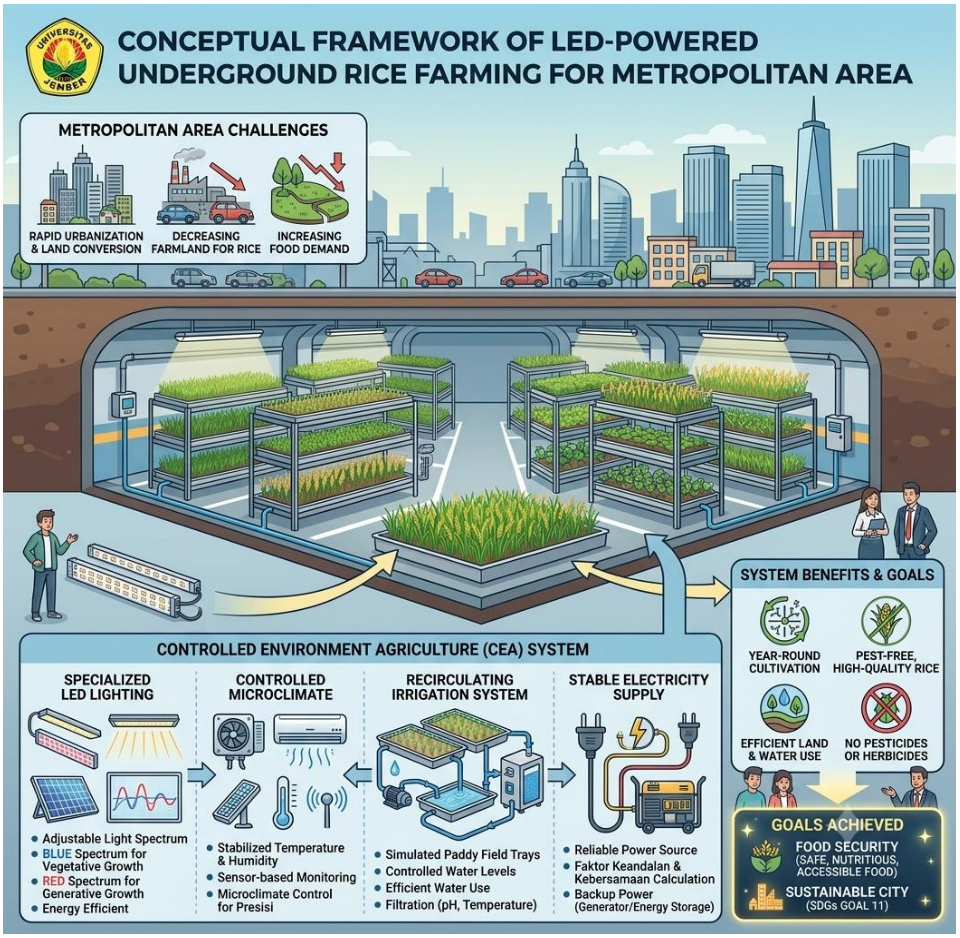

Fig. 1 Conceptual framework of LED-Powered Underground Rice Farming for Metropolitan Area

The underground cultivation space was designed to utilize underutilized urban infrastructures, including basements, underground facilities, and other subterranean spaces. This approach enables agricultural production without competing directly with urban surface land requirements. Environmental control technologies regulate temperature, humidity, and air circulation to maintain stable growing conditions throughout the production cycle. A recirculating irrigation system was incorporated to support semi-aquatic characteristics of rice cultivation while improving water-use efficiency. Unlike conventional paddy fields, water within the system can be continuously monitored, filtered, and reused. This design reduces water losses and contributes to efficient resources of food production [18].

The LED subsystem functions as the primary light source and provides customizable light spectra according to crop growth stages. Blue wavelengths support vegetative growth and leaf development, whereas red wavelengths stimulate photosynthetic activity and reproductive development [10], [11]. The integration of programmable LED systems enables precise environmental management and represents a key component of smart agricultural infrastructure. The resulting framework demonstrates how controlled environment technologies can be integrated into a single production system capable of supporting rice cultivation under metropolitan conditions characterized by severe land scarcity [8].

3.3 Resource Efficiency and Contribution to Smart Sustainable Cities

The analysis indicated that the proposed framework offers three major advantages like spatial efficiency, resource efficiency, and production stability. Underground farming significantly improves land use efficiency by transforming underutilized urban spaces into productive agricultural assets [12]. This finding supports recent studies [12], [18] which identified underground farming as a promising climate friendly urban agriculture strategy capable of reducing competition for surface land resources. The implementation of recirculating irrigation systems improves water reuse mechanisms reduce overall consumption while maintaining adequate growing conditions for rice plants. Similar observations have been reported in controlled environment agriculture studies, where water recycling technologies substantially reduced resource requirements without composing crop productivity.

The integration of LED technology enables year around production by eliminating dependence on seasonal variability and solar radiation availability. Previous studies demonstrated that optimized light spectra can improve photosynthetic efficiency and plant performance under controlled environments [17]. This capability is particularly important for metropolitan food systems where production continuity contributes directly to urban food resilience. Beyond agricultural benefits, the proposed framework aligns closely with smart city principles through the integration of environmental monitoring, resource optimization, and technology driven production management. Consequently, underground rice farming should be viewed not merely as an agricultural innovation but as an emerging component of resilient urban infrastructure capable of supporting sustainable city development.

3.4 Discussion and Scientific Contribution

The findings extend the current body of knowledge on underground farming in several important ways. Existing studies [14], [15], [16] have predominantly focused on vegetables, herbs, and microgreens due to their relatively short production cycles and lower environmental requirements. In contrast, this study explored feasibility of adapting underground farming principles to rice cultivation, a staple commodity with substantially different physiological and management requirements. The proposed framework also contributes to the growing literature on Controlled Environment Agriculture by introducing a systems-oriented approach that integrates spatial design, irrigation management, environmental regulation, and LED optimization into a unified production model. This differs from previous studies that generally examined these technological components separately.

This study introduces a novel conceptualization of underground farming as a strategic urban food infrastructure rather than merely an alternative cultivation technique. This perspective broadens the role of urban agriculture from local food supplementation toward supporting metropolitan food resilience under conditions of increasing land scarcity and urbanization. Nevertheless, several limitations remain. The framework developed in this study is conceptual and requires further empirical validation through pilot-scale implementation and techno-economic assessment. Future research should evaluate crop performance, energy consumption, production costs, and economic feasibility under operational conditions. Such investigations will be essential assessing the scalability of LED-powered underground rice farming in real metropolitan environments.

4. Conclusions

This study developed a conceptual and technical framework for LED-powered underground rice farming as an innovative approach to addressing agricultural land scarcity and strengthening urban food security in metropolitan areas. By integrating underground cultivation spaces, recirculating irrigation systems, environmental control mechanisms, and spectrum-adjusted LED lighting, the proposed framework demonstrated how controlled environment agriculture can be adapted to support staple crop production under highly constrained urban conditions. Unlike existing urban agriculture models that predominantly focus on horticultural commodities, this framework extended the application of underground farming to rice cultivation, thereby broadening the scope of controlled environment agriculture for strategic food production.

From a theoretical perspective, this study contributed to the growing discourse on sustainable urban agriculture by positioning underground rice farming as a component of resilient urban food infrastructure rather than merely an alternative cultivation technique. From a practical perspective, the proposed framework provides a reference for policymakers, urban planners, and agricultural stakeholders in designing technology-driven food production systems capable of improving land-use efficiency, resource optimization, and production resilience within smart and sustainable cities.

Nevertheless, this study was limited to the development of a conceptual framework based on qualitative synthesis and secondary data analysis. Consequently, the technical performance, economic feasibility, energy efficiency, and operational scalability of the proposed system require further empirical investigation. Future research should focus on pilot-scale implementation, techno-economic assessment, life cycle assessment, and the integration of Internet of Things (IoT), artificial intelligence (AI), and renewable energy technologies to evaluate the practicality of LED-powered underground rice farming under real metropolitan conditions. Such efforts will strengthen the evidence base for transforming innovative agricultural concepts into sustainable urban food production systems.

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