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Spatiotemporal Dynamics of Climate Indicators, Agricultural Human Resources, Ecological Resilience, and Irrigated Rice Productivity in Indonesia

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Abstract

Global climate change and extreme weather anomalies pose real challenges to the sustainability of irrigated rice farming in Indonesia. This study aims to analyze and map the spatial-temporal trends of four key variables over a five-year period (2022–2024) across 34 provinces in Indonesia, namely: (1) rainfall as a climate indicator, (2) the quality of agricultural human resources, (3) the Environmental Quality Index (IKLH) as a measure of ecological resilience, and (4) irrigated rice farm productivity. This study employs a quantitative approach using an exploratory descriptive method based on secondary panel data from the Central Statistics Agency (BPS) and the Meteorology, Climatology, and Geophysics Agency (BMKG). Trend analysis results indicate sharp and dynamic fluctuations in precipitation across all regions, with massive rainfall deficits occurring simultaneously in 2023 due to the El Niño phenomenon. The quality of agricultural human resources shows a positive and stable upward trend, though it is highly concentrated on the island of Java (scores of 64–68) compared to eastern Indonesia. Conversely, ecological

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resilience (IKLH) consistently recorded the highest scores in regions outside Java, particularly in Eastern Indonesia such as West Papua (>80). Meanwhile, irrigated rice productivity remained relatively stable in major production centers such as Bali (58–62 kw/ha) and Java, but experienced a temporary decline in various regions due to the drought in 2023. A comparative synthesis concludes that regions with high human resource quality and strong ecological resilience exhibit faster productivity recovery following climate shocks. These findings underscore the importance of policy interventions based on regional spatial-ecological characteristics in strengthening national food security.

Keywords: Spatial-Temporal Dynamics; Climate Change; Ecological Resilience; Trend analysis.

INTRODUCTION

Indonesia's agricultural sector, particularly irrigated rice farming, operates under increasingly high levels of environmental uncertainty. As an archipelagic nation located in the tropics, Indonesia is highly vulnerable to global climate variability and quasi-periodic phenomena such as the El Niño-Southern Oscillation (ENSO) (Ginting et al., 2026; Surmaini & Faqih, 2016) . Fluctuations in climate elements, particularly daily and annual rainfall, exert significant hydrometeorological pressure on the stability of the planting calendar, the availability of irrigation water, and the success of the physiological phases of rice plants. Given the high intensity of extreme weather anomalies over the past few years, mapping and a deep understanding of the spatial and temporal trajectories of climate trends have become crucial for the sustainability of national food security.

The impacts of climate change risks at the regional level do not occur in isolation but interact in complex ways with internal adaptive capacity and the quality of the regional environment (Febriosa et al., 2025; Pakidi & Tambaip, 2025; Qutbi et al., 2024). The quality of agricultural human resources reflected in technological literacy, educational attainment, health, and the absorption capacity of the agricultural labor force is the primary driver in determining the efficiency of farm management and the adoption of climate adaptation practices. On the other hand, according to Granata & Nunno (2026) , Mishra et al. (2025) , and Nehul(2026) , environmental carrying capacity and resilience reflected through ecological resilience play a strategic role as ecological buffers that mitigate extreme climate shocks, maintain the hydrological cycle, and preserve the functions of rice field ecosystems.

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Although national irrigated rice productivity has generally shown an upward trend, disparities and fluctuations in crop yields across the 34 provinces remain very evident. The peak of the El Niño phenomenon in 2023, for example, provides an empirical illustration of how climate shocks can suddenly reduce productivity figures in various provinces. Therefore, a comprehensive descriptive-spatial analysis of the trends and patterns in climate variables, the quality of agricultural human resources, ecological resilience, and irrigated rice productivity over the past three years (2022–2024) is crucial. This scientific article aims to conduct an in-depth analysis and mapping of the trends, fluctuation patterns, and spatial convergence correlations among these variables across all provinces in Indonesia.

RESEARCH METHOD

This study employs a quantitative approach using an exploratory descriptive method based on spatio-temporal analysis. This approach was chosen to map, describe, and analyze the patterns of development, fluctuations, and interregional disparities of the study variables over a specific time period without conducting experimental manipulation. The scope of the study covers 34 provinces in Indonesia, representing the diversity of national agroclimatic, demographic, and ecological characteristics. The unit of analysis in this study is provincial-level data observed over a three-year period from 2022 to 2024. This study focuses on four main variables: climate, the quality of agricultural human resources, ecological resilience, and irrigated rice productivity. The data used in this study are entirely quantitative secondary data. Data collection was conducted through documentation from the Central Statistics Agency (BPS) and the Meteorology, Climatology, and Geophysics Agency (BMKG).

Data analysis was conducted using descriptive and spatio-temporal statistical techniques, specifically by plotting the development trajectory of the data from 2022 to 2024 in a time series to identify movement patterns, upward/downward trends, and annual anomalies such as the impact of the El Niño phenomenon in 2023.

DISCUSSION

Climate Trends in Indonesia

The climate variable in this study is represented by annual rainfall data in millimeters, observed across 34 provinces in Indonesia over the past five years (2022–2024). Rainfall is an essential climatological indicator that reflects both water availability and the extent of hydrometeorological risk exposure faced by irrigated rice farming in each region. To provide a

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comprehensive empirical picture of these spatial and temporal distributions and fluctuations, rainfall trends across all provinces in Indonesia are visually presented through the following graphs and data summaries

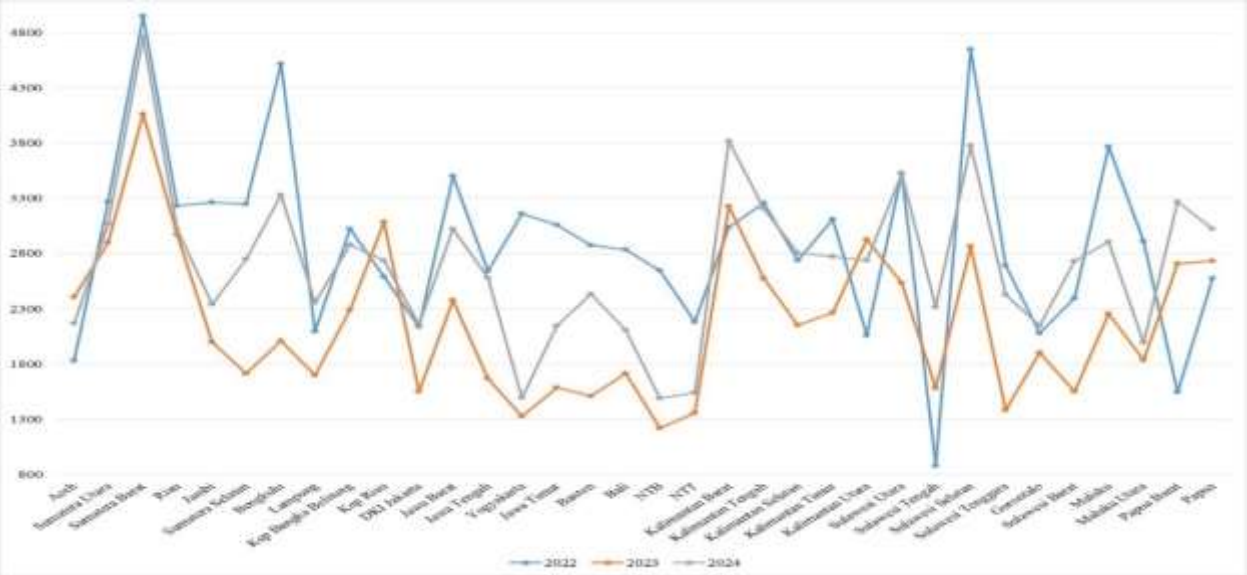


Figure 1. Spatial-Temporal Climate Analysis 2022–2024

The results of the spatial-temporal analysis indicate that climate indicators measured by annual rainfall (mm) across Indonesia's 34 provinces exhibited extremely sharp fluctuations and high variability during the 2022–2024 period. From 2022 to 2024, annual accumulated rainfall in most regions of Indonesia was observed to be very high due to the influence of a weak to moderate *La Niña* phenomenon, with provinces such as West Sumatra, West Java, Bengkulu, and South Sulawesi recording precipitation exceeding 4,000 mm per year. However, a massive and simultaneous nationwide decline in rainfall occurred in 2023 as a direct result of the peak of a strong El Niño event. Regions with a monsoon climate pattern experienced the most extreme rainfall deficits; West Nusa Tenggara (NTB) recorded a drop from 2,649.9 mm in 2022 to just 1,220.1 mm in 2023, followed by the Special Region of Yogyakarta, which saw a drastic decline from 3,161.2 mm to 1,327.73 mm. Similarly, the major rice-producing centers on the island of Java (Central Java, East Java, and Banten) experienced a decline in annual precipitation ranging from 35% to 50%. These conditions led to delays in the planting calendar and the threat of drought on rain-fed agricultural land. Entering 2024, precipitation levels across nearly all regions of Indonesia

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began to *rebound*, approaching normal levels.

Trends in the Quality of Agricultural Human Resources in Indonesia

The quality of agricultural human resources plays a crucial role as a key driver in determining the efficiency of farm management as well as the ability to adapt to environmental dynamics and climate change. This capacity encompasses educational attainment, technological literacy, technical skills, as well as labor force participation and employment rates in the agricultural sector. To provide a comprehensive empirical overview of the distribution, regional disparities, and development trajectory of agricultural s

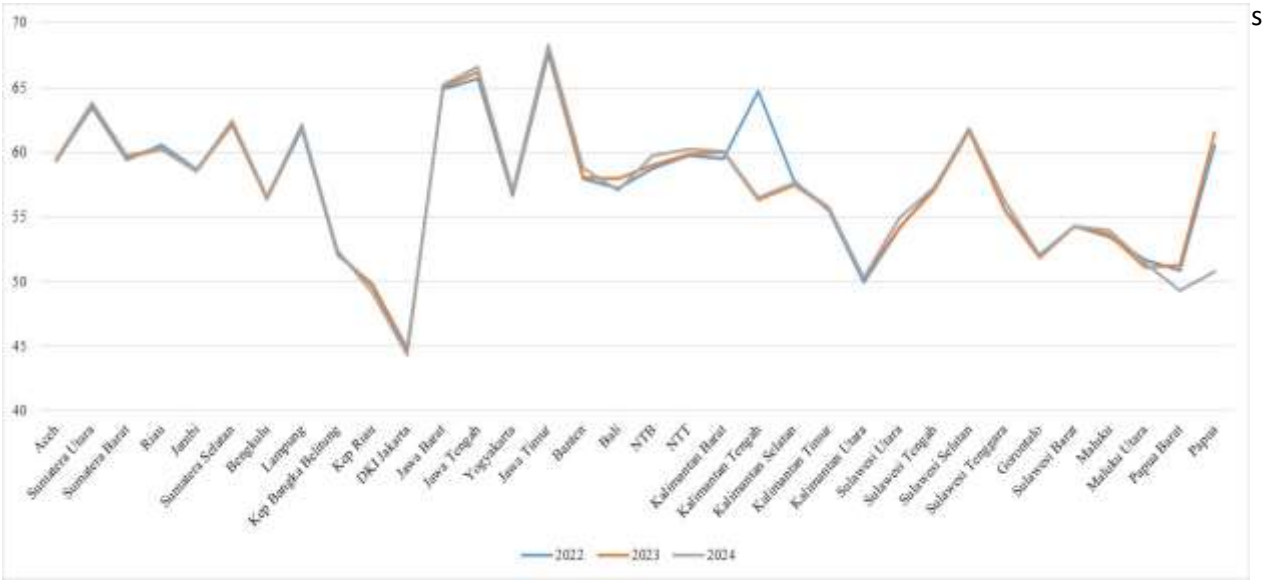


Figure 2. Spatio-Temporal Analysis of Agricultural Human Resource Quality, 2022–2024

The quality of agricultural human resources synthesized from indicators of education, technological literacy, health, and agricultural labor absorption shows a steady upward trend, though it is marked by quite striking spatial disparities across regions. Consistently, Java has dominated the highest agricultural human resource scores in Indonesia during the observation period. East Java Province recorded the highest score nationally, rising from 67.70 in 2022 to 68.33 in 2024, followed by Central Java (65.74 to 66.64) and West Java (64.88 to 65.23). The high agricultural human resource scores in Java were driven by strong participation in farmer organizations (Poktan/Gapoktan), easy access to agribusiness education facilities, and the rapid adoption of modern agricultural technologies. In contrast, regions outside Java, such as North Maluku (51.46 in 2024), West Papua (49.31 in 2024), and the Riau Islands (49.13 in 2024), still record relatively low agricultural human resource scores. This indicates the presence of structural

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constraints regarding the recruitment of young farmers, the level of formal education among the agricultural workforce, and the limited reach of agricultural extension services in island regions and Eastern Indonesia

Trends in Irrigated Rice Productivity in Indonesia

Rice paddy farm productivity is a key indicator reflecting the effectiveness of technological interventions, the quality of environmental carrying capacity, and the adaptive capacity of agricultural human resources at the regional level. The level of yield per hectare not only reflects technical production efficiency but also the physical vulnerability of crops to climate anomalies and extreme weather events. To provide an empirical overview of the magnitude of achievements, the level of annual fluctuations, and disparities in irrigated rice productivity across provinces in Indonesia during the observation period, the development of these spatiotemporal data is presented visually through the following graphs and summaries.

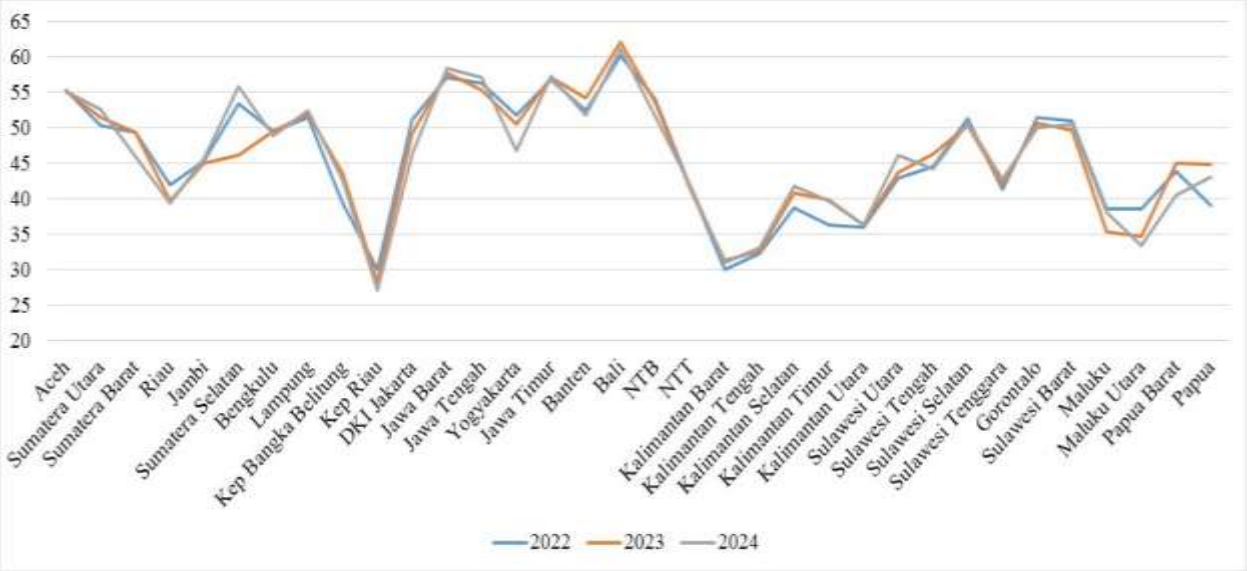


Figure 3. Spatio-Temporal Analysis of Irrigated Rice Productivity, 2022–2024

Irrigated rice productivity (quintals/hectare) across 34 provinces exhibits diverse dynamics that are heavily influenced by the interaction between weather shocks, the adaptive capacity of human resources, and the support of local ecological conditions . Bali Province has consistently recorded the highest irrigated rice productivity in Indonesia, ranging from 60.27 kw/ha in 2022 to 61.22 kw/ha in 2024, supported by efficient water management through the Subak customary institution. The major national rice-producing centers on the island of Java (West Java, Central

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Java, and East Java) also succeeded in maintaining high productivity in the range of 55.30 to 58.47 kw/ha. Although affected by El Niño in 2023, the decline in productivity on Java was relatively contained (<3%) and recovered quickly by 2024. A significant drop in productivity due to the 2023 El Niño-induced drought was observed in South Sumatra, where productivity plummeted from 53.45 kw/ha (2022) to 46.19 kw/ha (2023), before eventually rebounding to 55.83 kw/ha in 2024. On the other hand, regions with marginal soils and island areas such as the Riau Islands (26.99–30.00 kw/ha) and West Kalimantan (29.94–31.25 kw/ha) consistently recorded the lowest productivity due to limited technical irrigation and high soil acidity levels.

Trends in Ecological Resilience in Indonesia

Ecological resilience variables, represented by the Environmental Quality Index, play a strategic role as ecological buffers that mitigate environmental pressures, maintain the hydrological cycle, and preserve the balance of ecosystems supporting agriculture. The level of environmental quality reflects a region's carrying capacity in addressing vulnerabilities to global climate change. To provide an empirical overview of the magnitude of achievements, spatial distribution patterns, and dynamics of ecological resilience levels across various provinces in Indonesia during the observation period, the development of this spatiotemporal data is visually presented through the following graphs and summaries

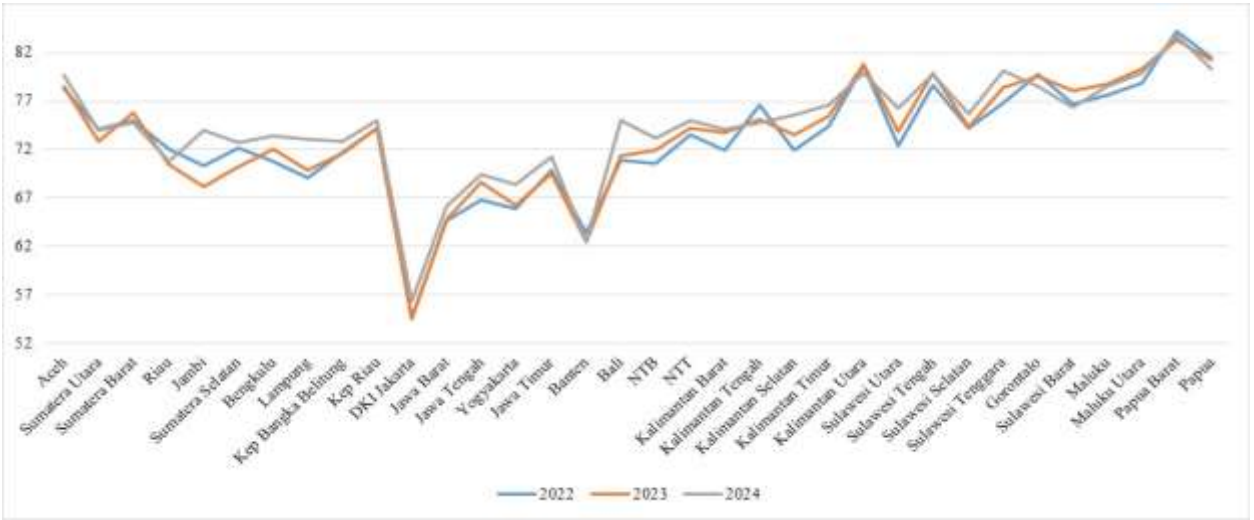


Figure 4. Spatial-Temporal Analysis of Ecological Resilience, 2022–2024

Source: Secondary Data, After Processing

The level of a region's ecological resilience as measured by the Environmental Quality Index, which encompasses water quality, air quality, and land cover exhibits a spatial distribution

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pattern that is the inverse of the distribution of agricultural human resource quality. Regions outside Java, particularly Eastern Indonesia and Kalimantan, recorded exceptionally high ecological resilience scores that remained consistently high throughout the 2020–2024 period. West Papua consistently leads the nation in EQI scores, ranging from 83.31 to 84.22, followed by Papua (80.32–81.46), North Kalimantan (79.95–80.77), Gorontalo (78.50–79.79), and North Maluku (78.84–80.36). The high IKLH scores in these regions reflect the continued preservation of natural forest cover and water absorption functions within watersheds (DAS), which serve as crucial ecological buffers in mitigating the impacts of climate shocks. In contrast, the island of Java falls into the moderate-to-low category, as seen in Banten Province (62.54 in 2024) and West Java (66.09 in 2024), which are under pressure from the high rate of conversion of agricultural land into residential and industrial areas, as well as the intensity of environmental pollution

DISCUSSION

Overall, the empirical findings of this study confirm that the resilience of irrigated rice farm productivity to the threats of climate change results from the convergent interaction between the level of threat exposure, the adaptive capacity of human resources, and environmental carrying capacity. The vulnerability of the agricultural sector triggered by extreme weather anomalies cannot be mitigated through a single dimension alone but requires a synergistic combination of social-technological capital and the region's ecological carrying capacity. These findings align with empirical studies conducted by Umanailo (2026) and Budiman & Suhendi (2024), which affirm that the resilience of the national food system is highly dependent on the level of local adaptability in responding to macro-scale climate shifts. Spatial-temporal consistency over the 2022–2024 period demonstrates that regions with strong systemic preparedness are better able to mitigate the impacts of climate fluctuations in a more measured manner.

Regions with high agricultural human resource scores, such as Java and Bali, were shown to have a faster capacity for mitigation and adaptation when facing massive drought shocks in 2023. High levels of literacy and access to technology enabled farmers in these regions to promptly adopt water-efficient irrigation technologies, accelerate mechanized soil preparation, and use drought-tolerant rice varieties. This is supported by research by Prasar et al.(2024) , Shiferaw(2014) , and Kolapo et al.(2026) , which found that the adoption of adaptive technological innovations and the strengthening of farmer institutions such as Subak in Bali and Gapoktan in Java were key determinants in accelerating productivity recovery following extreme drought shocks . The internal capacity of human resources acts as *a shock absorber* that significantly

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mitigates declines in rice *yields*.

Meanwhile, regions outside Jawa such as South Sulawesi, Gorontalo, and West Nusa Tenggara leverage their ecological resilience as a natural buffer that provides groundwater supplies and river flows to minimize the risk of crop failure. Although the agricultural human resource score in these regions falls into the medium category, the availability of ecological buffers supports the sustainability of the agricultural hydrological cycle. This dynamic aligns with the findings of studies by Jia et al.(2026) and Bera & Dutta (2024) , which highlight that areas with a high Environmental Quality Index possess better agricultural ecosystem resilience against hydrometeorological pressures. Based on this synthesis, the strategic policy implications confirm that strengthening national food security cannot be approached with a one-size-fits-all approach. The island of Java requires policies to protect the Environmental Quality Index (IKLH) and halt the conversion of technically viable rice fields, while regions outside Java need to accelerate the development of agricultural human resources and irrigation infrastructure to optimize their still-enormous environmental carrying capacity.

CONCLUSION

Based on the results of the spatio-temporal analysis for the 2022–2024 period, this study concludes that the resilience of irrigated rice farm productivity in Indonesia to the dynamics of climate change is influenced by the convergent interaction between precipitation variability, the adaptive capacity of agricultural human resources, and regional ecological carrying capacity. The El Niño climate anomaly in 2023 was found to have caused hydrometeorological shocks that reduced precipitation and productivity nationwide; however, the impacts and the speed of recovery exhibited significant spatial variation. Regions with high-quality agricultural human resources, such as Java and Bali, have demonstrated a faster adaptive response through the efficient modernization of technology, its application in irrigation management, and the strengthening of local institutions. Conversely, regions outside Java, such as Eastern Indonesia, demonstrated a high Environmental Quality Index, which plays a crucial role as a natural ecological buffer in maintaining water supplies and mitigating the risk of crop failure. Thus, the success in maintaining the stability of national paddy field productivity cannot be achieved through a single aspect alone, but rather through synergy between the technological capacity of human resources and the sustainability of environmental carrying capacity in each region.

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