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RESEARCH ARTICLE
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Industrial Encroachment and Agricultural Sustainability: A Multidimensional Study of Rice Farming in West Java

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ABSTRACT

This study assesses the sustainability of rice farming in Cirebon District, West Java, Indonesia, an area increasingly affected by the expansion of the natural stone industry. Using the RAP-Rice method, an adaptation of the RAPFISH approach based on Multidimensional Scaling (MDS), the study evaluates five sustainability dimensions: economic, social, ecological, technological, and institutional. Data were collected from farmer surveys, field observations, interviews, and government reports. Results show that all five dimensions fall within the moderate sustainability range, with index scores between 51.55 and 52.39. Leverage analysis identifies key factors driving sustainability, including profitability, youth involvement, irrigation maintenance, organic fertilization, and access to extension services. Monte Carlo simulations confirm the robustness and consistency of the MDS results, with low stress values and high RSQ scores across dimensions. These findings underscore the need for integrated policies that focus on internal system improvements to enhance agricultural resilience in industrially encroached areas. The study offers practical insights for policymakers and local governments seeking to support rice farmers through infrastructure, institutional, and environmental interventions.

Keywords: RAP-rice, Sustainability assessment, Rice farming, Industrial encroachment, Cirebon

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INTRODUCTION

Sustainable agriculture is increasingly central to global development discourse, particularly in response to mounting pressures from population growth, climate change, land use conflicts, and natural resource degradation (Khan et al., 2022). The imperative to balance economic development with environmental preservation has propelled research towards multidimensional assessments of agricultural sustainability, especially in contexts where farming systems are exposed to complex socio-environmental stressors. This concern is especially acute in Indonesia, where agriculture continues to serve as a critical economic sector and a cornerstone of national food security (Maspul, 2024). As the world's third-largest rice producer, Indonesia relies heavily on rice farming for both rural livelihoods and national food sovereignty (Setiartiti, 2021). Within this landscape, West Java particularly Cirebon Regency plays a pivotal role in national rice production. However, the sustainability of rice farming in this region is increasingly under threat due to the rapid expansion of industrial activities, most notably the natural stone industry. Although this industry contributes to local economic growth, it has also been associated with severe environmental degradation, including soil erosion, water pollution, and biodiversity loss (Ekka at al., 2023). Sediment and waste discharge into irrigation channels have been shown to alter water pH, reduce transparency, and disrupt nutrient balances, ultimately impairing rice yields and undermining ecosystem stability.

While recent scholarship has begun to explore the environmental implications of industrial activity in agricultural zones (Raihan & Tuspecova, 2022), a critical gap remains in the development of integrated sustainability assessment frameworks. Most studies in the Indonesian context tend to focus narrowly on either biophysical degradation or economic variables, such as declining farm incomes (Hariyanto at al., 2025). However, such uni-dimensional approaches overlook the interdependent nature of sustainability, particularly the social, institutional,

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and technological factors that also shape farming resilience. As a result, policy recommendations based on these studies are often fragmented and insufficient for addressing the multifaceted challenges faced by farmers in industrially encroached areas (Adebayo, 2024).

To overcome these limitations, scholars have increasingly turned to tools such as the RAPFISH framework and its agricultural adaptations (e.g., RAP-Agri, RAP-Rice), which employ Multidimensional Scaling (MDS) techniques to evaluate sustainability across five key domains: ecological, economic, social, institutional, and technological (Safriyana, 2023; Karyani et al., 2024; Sia et al., 2025). These methods allow for a more holistic representation of sustainability by quantifying interrelated indicators and identifying sensitive leverage points. Despite their growing use in fisheries and broader agricultural settings, such frameworks remain underutilized in rice farming systems exposed to direct industrial pressures.

This study addresses this critical gap by applying the RAP-Rice method to assess the multidimensional sustainability of rice farming in Cirebon District, where natural stone extraction and processing directly interact with agricultural land and water systems. The objectives of the study are threefold: to evaluate the current sustainability status of rice farming under industrial stress, to identify leverage attributes that most influence sustainability outcomes, and to offer policy-relevant recommendations for enhancing agricultural resilience. By doing so, this research contributes not only to methodological advancement but also to sustainable land-use governance in contested rural regions of Indonesia.

MATERIALS & METHODS

Study Area

This research was conducted in Cirebon District, located in the eastern part of West Java Province, Indonesia. Cirebon is widely recognized as one of the key rice-producing regions in Java, supported by fertile volcanic soils, well-established irrigation infrastructure, and a strong cultural legacy of rice cultivation. However, in recent years, the region has also emerged as a center for the natural stone industry, particularly in subdistricts such as Palimanan, Depok, and Dukupuntang. These subdistricts, which serve as the primary research locations in this study, have experienced intensified quarrying and stone processing activities that frequently occur in close proximity to irrigated paddy fields.

The growth of the stone industry has introduced significant challenges to local agricultural systems, including soil degradation, water pollution, and reduced access to productive land. These pressures are particularly acute in areas where stone sediment discharge has altered water quality in irrigation canals, directly impacting farming conditions. The dual economic character of Cirebon functioning as both an agricultural and industrial hub makes it a compelling case for assessing agricultural sustainability under spatial and environmental stress.

The selected research locations Palimanan, Depok, and Dukupuntang are situated in developing to developed subdistricts, as indicated in Fig. 1, which illustrates the spatial classification of city development levels in Cirebon. The map also highlights the positioning of the study sites using geotag markers. These areas represent zones where industrial expansion intersects most directly with rice cultivation, offering relevant insights into the ecological, economic and institutional dynamics shaping sustainability outcomes.

Research Design

This study employed a quantitative case study approach to assess the sustainability of rice farming in areas affected by the natural stone industry in Cirebon Regency, West Java, Indonesia. The research utilized the Rapid Appraisal for Rice (RAP-Rice) methodology, which is based on Multidimensional Scaling (MDS), to evaluate sustainability across five key dimensions: ecological, economic, social, institutional, and technological. This approach allows for a comprehensive analysis of sustainability by integrating various indicators and assessing their interrelationships.

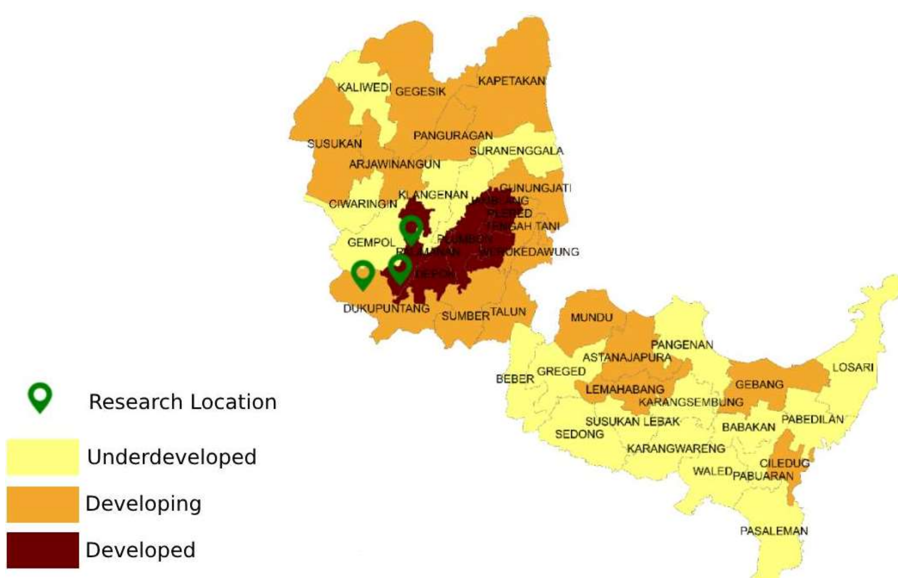

Fig. 1: Research locations.

The RAP-Rice method is an adaptation of the RAPFISH technique, initially developed for fisheries sustainability assessments, and has been effectively applied in agricultural contexts, including rice farming. It involves scoring a set of predefined attributes within each sustainability dimension, followed by MDS analysis to generate sustainability indices and identify leverage factors. This methodology facilitates the identification of sensitive attributes that significantly influence the sustainability status, providing valuable insights for policy and decision-making.

By applying the RAP-Rice approach in the context of Cirebon Regency, this study aims to capture the complex interactions between rice farming practices and the environmental impacts of the natural stone industry. The findings are intended to inform strategies for enhancing the sustainability of rice farming in regions experiencing similar industrial pressures.

The analytical procedure employed in this study is summarized in the conceptual framework below (Fig. 2), which illustrates the RAP-Rice methodology applied to evaluate the sustainability of rice farming systems in Cirebon.

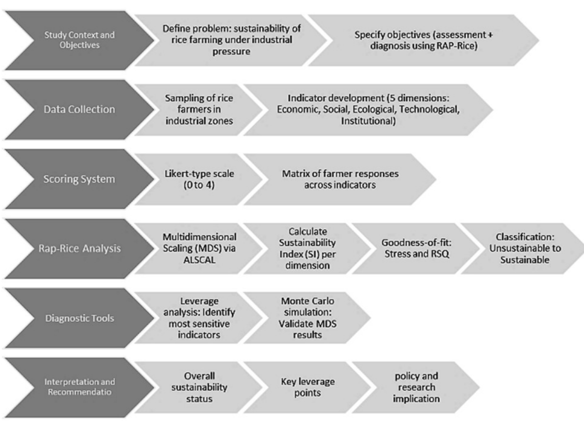

Fig. 2: Conceptual Framework.

Data Collection

The data collection process for this study was designed to comprehensively assess the sustainability of rice farming in areas influenced by the natural stone industry in Cirebon District. A combination of primary and secondary data sources was utilized to capture both quantitative and qualitative aspects of the farming systems under study. Primary data were collected through structured surveys administered to 338 rice farmers operating near natural stone processing sites. These surveys aimed to gather detailed information on farming practices, input usage, yield levels, income, labor dynamics, and perceptions of environmental changes. In addition to the surveys, direct field observations were conducted to document the physical condition of rice fields, irrigation infrastructure, and visible signs of environmental degradation, such as sediment accumulation or water discoloration. Key informant interviews were also conducted with local agricultural extension officers, farmer group leaders, and representatives from relevant government agencies to gain insights into institutional support mechanisms, policy implementation, and community responses to industrial activities.

Secondary data sources complemented the primary data collection. These included agricultural production statistics from the Badan Pusat Statistik (BPS), environmental quality reports from local environmental agencies, and land use maps indicating the spatial distribution of natural stone industry operations and agricultural areas. The integration of these diverse data sources provided a robust foundation for evaluating the multidimensional sustainability of rice farming in the context of industrial pressure. By combining quantitative measurements with qualitative insights, the study was able to capture the complex interplay between environmental, economic, social, institutional, and technological factors affecting agricultural sustainability in Cirebon Regency.

Sampling Technique

This study employed a purposive sampling strategy to select rice farming households in Cirebon District, specifically within subdistricts affected by the expansion of the natural stone industry. Although the study aimed for broad representation, the selection process was not purely random. Instead, respondents were intentionally chosen based on defined eligibility criteria to ensure contextual relevance to the research objectives. This clarification addresses the inconsistency in the original description and better reflects the applied methodology. The sampling frame included three subdistricts Palimanan, Depok, and Dukupuntang which were identified through preliminary field mapping and stakeholder consultations as areas with both direct and indirect exposure to industrial activity. These locations are characterized by the close spatial relationship between stone quarrying operations and irrigated rice farming zones, with some irrigation systems visibly affected by sediment discharge and pollution.

Respondents were selected based on the following criteria: 1) Active involvement in rice farming for at least the past three years; 2) Use of irrigation water systems that are potentially impacted by industrial runoff; 3) Residence within the selected subdistricts to ensure long-term exposure and contextual familiarity. A total of 338 rice farmers were included in the final sample. This sample size was determined based on practical field considerations and guided by prior RAP-based studies, which recommend sample sizes of at least 250 respondents to ensure stable sustainability assessments across multiple dimensions (e.g., ecological, economic, social). The sample was designed to capture a diversity of farm sizes, socioeconomic backgrounds, and levels of institutional engagement.

Both individual farmers and members of local farmer groups were included to enable analysis of both household-level decision-making and collective adaptation strategies. The purposive nature of the sampling also allowed for the inclusion of informants with experience in farmer cooperatives and access to extension services, thus enriching the study’s capacity to analyze social and institutional dimensions of sustainability under industrial pressure.

Sustainability Indicators and Dimension

This study adopts a multidimensional framework for assessing the sustainability of rice farming by employing the RAP-Rice method, an adaptation of the RAPFISH approach tailored for agricultural contexts. The analysis is structured around five core dimensions of sustainability ecological, economic, social, institutional, and technological each represented by three contextually relevant indicators. These indicators were developed based on existing literature, expert consultations, and prior RAP-based sustainability assessments applied in agricultural systems. The ecological dimension includes three indicators that reflect environmental quality and resilience (Meuwissen et al., 2019). These indicators assess whether environmental factors are integrated into rice farming decision-making, whether irrigation channels are regularly maintained to anticipate water surplus or shortage, and whether the expansion of the natural stone industry has led to the opening of new rice fields as a compensatory response to land degradation.

The economic dimension also comprises three indicators, focusing on economic efficiency as measured through profitability calculations, net returns from rice farming, and the extent to which the stone industry or government provides financial assistance to farmers (Alam et al., 2022). These variables reveal the overall economic viability and external support mechanisms within the farming system. The social dimension contains three indicators that capture key elements of social sustainability in farming communities (Hua et al., 2024). These include the presence of an intergenerational mandate or expectation to continue rice farming, the active involvement of youth in the rice farming sector, and the frequency of land-use conflicts between rice farmers and the natural stone industry.

The technological dimension is composed of three indicators that reflect the availability and responsiveness of technological innovations to environmental stressors (Ahmad et al., 2023). These include increases in rice productivity, the growing necessity for organic fertilizer to restore soil fertility due to industrial waste (IBA), and the extent to which farmers experiment with new cultivation technologies to mitigate IBA-related impacts. Finally, the institutional dimension (referred to as organizational) comprises three indicators focusing on governance and institutional support (Stringer et al., 2020). These indicators assess the importance of farmer participation in agricultural groups, the presence of agricultural extension services, and the existence of regional policies ensuring permanent land status for rice farming areas. Each indicator is scored using a Likert-type scale ranging from 0 (least sustainable) to 4 (most sustainable), based on triangulated data from farmer responses, field observations, and expert validation. In total, this study utilizes 15 sustainability indicators distributed evenly across five dimensions. These indicators serve as the basis for the subsequent Multidimensional Scaling (MDS) analysis, which quantifies overall sustainability status and identifies the most influential leverage points for targeted policy intervention.

Data Analysis Technique

The analysis of rice farming sustainability in this study was conducted using the RAP-Rice method, which applies Multidimensional Scaling (MDS) to convert qualitative assessments into quantitative scores across five sustainability dimensions: ecological, economic, social, institutional, and technological. This technique enables a rapid yet structured evaluation by organizing complex interrelations among indicators into a spatial configuration, which allows for visualizing the relative sustainability of farming systems. The process began by scoring each sustainability indicator using a five-point Likert-type ordinal scale. A score of 0 indicates the least sustainable condition, while a score of 4 represents the most sustainable. These ordinal scores were compiled into a data matrix, where rows represent individual farmer observations and columns represent the 15 sustainability indicators. The MDS algorithm then processed this matrix using the ALSCAL (Alternating Least Squares Scaling) procedure, which determines the positioning of each case in a low-dimensional space based on similarity or dissimilarity in indicator scores. To standardize these results, a Sustainability Index (SI) was calculated for each dimension. This index transforms the raw MDS scores into a 0 to 100 scale, allowing for easier interpretation and cross-dimensional comparison. The formula used is:

$$SI = \frac{X - X_{min}}{X_{max} - X_{min}} \times 100$$

Where:

SI = Sustainability Index (0 to 100 scale)

X = MDS Score of the dimension

X_{min} and X_{max} = Minimum and maximum possible scores for the dimension

The resulting index values were then classified into four categories of sustainability status (Table 1):

Table 1: Four Categories of Sustainability

Score	Classifications
0-25	Unsustainable
25.01-50	Poor
50.01-75	Moderate
65.01-100	Sustainable

To identify the most influential indicators, a leverage analysis was performed. This involved simulating a one-unit change in the score of each attribute while holding others constant and observing the resulting effect on the MDS configuration. Attributes with the highest Root Mean Square (RMS) changes were identified as sensitive and prioritized as leverage points for policy intervention.

In addition, Monte Carlo analysis was employed to test the robustness of the MDS configuration. This involved repeating the MDS procedure with randomized perturbations of the input data to assess stability. A low standard deviation between real and simulated index values indicates a high level of robustness and internal consistency in the model output. Overall, this analytical framework allowed the study to generate both a composite measure of sustainability and detailed diagnostic insights into the specific indicators that most critically affect the sustainability of rice farming systems in the study area.

RESULTS

Descriptive Statistics

Table 2 presents two sets of baseline data: (1) the socio-demographic characteristics of rice farmers and (2) subdistrict-level rice production statistics in areas affected by the natural stone industry in Cirebon District. For clarity, these categories are discussed separately to highlight distinct but interrelated factors shaping sustainability.

Table 2: Respondent Profile and Study Area

Variable	Category	Percentage / Value
Age of Respondents	23–64 years	72%
	>64 years	28%
Education Level	Did not complete elementary (SD)	76%
	Junior High School (SMP)	10%
	Senior High School (SMA)	13%
	Undergraduate (S1)	1%
Number of Family Dependents	0–2 people	44%
	2–4 people	40%
	5–6 people	11%
	More than 7 people	5%
Subdistrict	Depok	
Planted Area		1,675ha
Harvested Area		1,675ha
Rice Production		11,658tons
Subdistrict	Dukupuntang	
Planted Area		3,660ha
Harvested Area		3,660ha
Rice Production		24,419tons
Subdistrict	Palimanan	
Planted Area		2,298ha
Harvested Area		2,263ha
Rice Production		16,917tons

The age distribution of respondents shows that 72% are within the productive age range of 23 to 64 years, indicating that the region's rice farming remains largely managed by active working-age adults. However, 28% of farmers are above 64 years old, underscoring the demographic aging of the farming population. This trend raises significant concerns about intergenerational succession, as the declining participation of younger generations may reduce the long-term viability of farming in the region. Sustainability could be compromised if knowledge transfer and youth engagement are not supported by targeted policy measures. Education levels among respondents are also notably low. Approximately 76% did not complete elementary school, while only 1% attained undergraduate education. This limited access to formal education may hinder the adoption of sustainable agricultural practices, such as the use of organic inputs or adaptive irrigation methods, which often require basic technical literacy. The low education levels could also constrain farmers' participation in government programs, training sessions, and institutional innovations aimed at improving agricultural resilience.

Household dependency data further illustrate the socio-economic context. About 40% of farmers are responsible for 2 to 4 dependents, while 44% support up to 2 individuals. This variation in household size indicates differing levels of economic pressure and labor availability, which may influence farmers' willingness or ability to invest in long-term sustainability practices. Rice production data from the three study subdistricts, Depok, Dukupuntang, and Palimanan highlight ongoing agricultural activity in the face of expanding industrial encroachment. Dukupuntang recorded the largest planted and harvested areas, totaling 3.660hectares, and the highest rice output at 24.419tons. Palimanan followed with 2.298 hectares planted and 16.917tons produced, while Depok had the smallest agricultural coverage at 1.675hectares and a total output of 11.658tons. These Fig.s reflect the continued economic and food security importance of rice farming in the region. However, the observed variation in land area and production volumes may also signal uneven exposure to environmental degradation and differing levels of adaptive capacity. Subdistricts more heavily impacted by stone quarrying activities may experience greater reductions in available land and irrigation quality, potentially limiting output over time. Overall, these descriptive findings reveal a complex socio-environmental context characterized by an aging and low-educated farming population operating under mounting industrial pressure. These conditions underscore the importance of integrating social and economic dimensions into sustainability planning and provide a critical foundation for the multidimensional assessment presented through the RAP-Rice framework.

Sustainability Status

The sustainability assessment of rice farming in the natural stone industrial zones of Cirebon District was conducted using the RAP-Rice method across five key dimensions: economic, social, ecological, technological, and institutional (organization). The results, presented in the radar diagram (Fig. 3), indicate that all five dimensions fall within the moderate sustainability category, with index values ranging between 51.55 and 52.39 on a 0–100 scale.

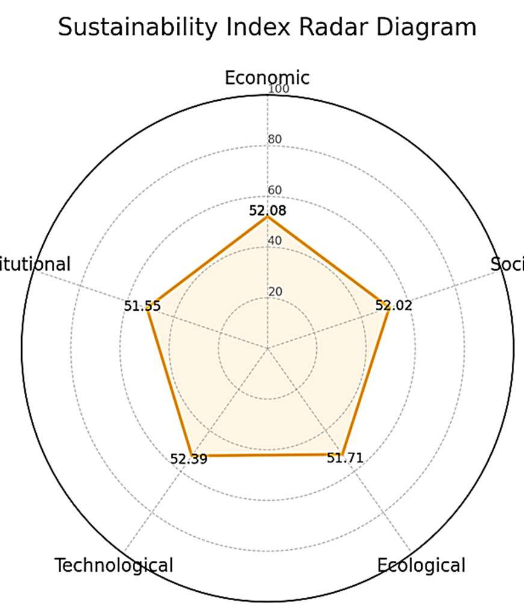

Fig. 3: Radar Chart Visualizing the Sustainability Index.

Among the five dimensions, the technological dimension achieved the highest sustainability index score of 52.39, suggesting that farmers in the region have a relatively favorable level of access to agricultural technology, including mechanization, improved seed varieties and irrigation tools. This finding aligns with prior studies that highlight the role of technological access in enhancing agricultural productivity and adaptive capacity (Gamage et al., 2024; Sulfiana, 2025). A moderate capacity for innovation suggests that despite environmental pressures, the local farming system retains a degree of resilience through technology adoption. The economic dimension, with a score of 52.08, indicates a moderately sustainable condition in terms of productivity, income, cost management, and market access. This reflects a situation where farmers can still derive economic returns from rice cultivation, although the proximity of the stone industry has not notably improved or worsened their financial outcomes. Similar results were observed by Guiling et al. (2009), who reported that industrial proximity does not always correlate with economic benefits for adjacent agricultural communities. Nevertheless, the looming risk of resource competition and shifts in land value due to industrial expansion remains a concern (Adam, 2023; Hatidja et al., 2025). The social dimension scored 52.02, reflecting a generally stable but vulnerable social structure. The high proportion of elderly farmers and low education levels observed in the respondent profile are consistent with national rural demographic trends, which pose challenges to long-term sustainability and intergenerational knowledge transfer (Shahen et al., 2021). These findings underscore the social fragility often embedded in aging agrarian communities, which may hinder adaptation to future shocks or innovation uptake. The ecological dimension recorded a slightly lower score of 51.71, drawing attention to moderate but notable environmental sustainability concerns. Reports of sediment contamination and soil degradation caused by waste from the stone processing industry are consistent with past studies highlighting the ecological risks of unregulated industrial activities near farmlands (Li et al., 2022; Padhiary & Kumar, 2024; Farishi et al., 2025). Although degradation has not yet crossed critical thresholds, the risk of cumulative impact remains significant without targeted environmental management.

Lastly, the institutional or organizational dimension scored 51.55, the lowest among the five, yet still within the moderate range. This reflects limited access to agricultural extension services, ambiguous land tenure arrangements, and insufficient policy coordination. These institutional shortcomings resonate with findings from similar contexts where weak governance has undermined the integration of agricultural and industrial land-use planning (Day et al., 2022; Agir et al., 2023; Alam, 2025). Strengthening institutional mechanisms and improving cross-sectoral governance is therefore critical to enhance farmer protection and long-term sustainability. Overall, the findings indicate that rice farming in the study area maintains a moderate level of sustainability across all dimensions, with only marginal differences in index values. While no single dimension is critically unsustainable, the analysis reveals potential vulnerabilities that could worsen if left unaddressed. This calls for coordinated improvements, particularly in institutional support and environmental management, to enhance the system's resilience. The following leverage analysis will further identify which factors exert the greatest influence on sustainability outcomes and should therefore be prioritized in policy interventions.

Overall Sustainability Index

The overall sustainability status of rice farming systems located within the natural stone industry zones in Cirebon District was assessed using the RAP-Rice methodology, which evaluates five dimensions: economic, social, ecological, technological, and institutional. The results indicate that all five dimensions fall within the moderate sustainability category, with index scores ranging from 51.55 to 52.39, as shown in Table 3. Among the assessed dimensions, the technological dimension recorded the highest sustainability index at 52.39, reflecting relatively favorable access to agricultural technologies, including improved seeds, irrigation infrastructure, and basic mechanization. This suggests that farmers possess moderate capacity for innovation and adaptation despite increasing environmental and land-use pressures. The economic and social dimensions followed closely, with scores of 52.08 and 52.02, respectively, indicating modest levels of profitability, input efficiency, and social cohesion, although signs of vulnerability remain.

Table 3: Sustainability Index Summary

Dimension	Sustainability Index	Status	Stress	RSQ
Economic	52.08	Moderate	0.1853	0.9239
Social	52.02	Moderate	0.1868	0.9232
Ecology	51.71	Moderate	0.1869	0.9229
Technology	52.39	Moderate	0.1857	0.9235
Organization	51.55	Moderate	0.1870	0.9229
Overall	52.01 (avg.)	Moderate	—	—

The ecological dimension, scoring 51.71, points to moderate sustainability but highlights emerging concerns over water contamination, sedimentation, and soil degradation, all of which are associated with industrial encroachment. The institutional dimension, with the lowest score at 51.55, reveals constraints in access to extension services, land tenure security, and responsiveness of local governance, which may limit the capacity for systemic sustainability improvements. In addition to the index scores, Table 3 also presents the goodness-of-fit metrics generated from the Multidimensional Scaling (MDS) analysis. All five dimensions yielded Stress values below 0.19, which fall well within the acceptable range (below 0.25), indicating reliable spatial configurations. Furthermore, the RSQ (R-squared) values exceeded 0.92 for all dimensions, confirming that the MDS configuration explained over 92% of the variance in the data. These results demonstrate excellent internal consistency and robustness, reinforcing the validity of the RAP-Rice model used in this study.

The performance across dimensions is summarized in Table 3. The overall sustainability index, calculated as the unweighted average of all five dimensions, was 52.01, confirming that rice farming in the study area is currently situated within the moderate sustainability range. Although the values are not critically low, their narrow dispersion and proximity to the lower threshold highlight the system's fragility and the urgent need for targeted interventions. The following section presents the results of the leverage analysis to identify which indicators exert the greatest influence on sustainability outcomes and should therefore be prioritized in policy strategies.

Leverage Analysis Result

To identify the most influential factors shaping the sustainability of rice farming systems in the natural stone industry zones of Cirebon District, a leverage analysis was performed for each sustainability dimension (Fig. 4). Leverage values represent the Root Mean Square (RMS) change in ordination scores when an attribute is removed, indicating its sensitivity and contribution to the overall sustainability index. Attributes with higher leverage values are considered more critical and are thus strategic points for targeted intervention.

In the economic dimension, the attribute with the highest leverage value was "profitability of rice farming" (5.75), followed by "economic efficiency" (3.90), while "economic assistance from the stone industry and government" had the lowest impact (0.53). This suggests that farmer income derived from agricultural productivity plays a more significant role in sustainability outcomes than external financial support, which is currently either limited or ineffective. Policies aimed at improving profitability through better market access, cost reduction, or price stability are likely to generate greater sustainability gains than subsidies alone. Within the social dimension, the attribute with the strongest influence was "youth involvement in rice farming" (5.24), indicating that generational continuity is a key concern in the region. "Mandate or expectation to continue farming" (3.91) was also an important driver, while "land use conflict with the stone industry" exerted minimal leverage (0.18). These results imply that while land conflict is perceived, it is not the most pressing social determinant of sustainability. Instead, ensuring that younger generations remain engaged in agriculture is essential for long-term social viability.

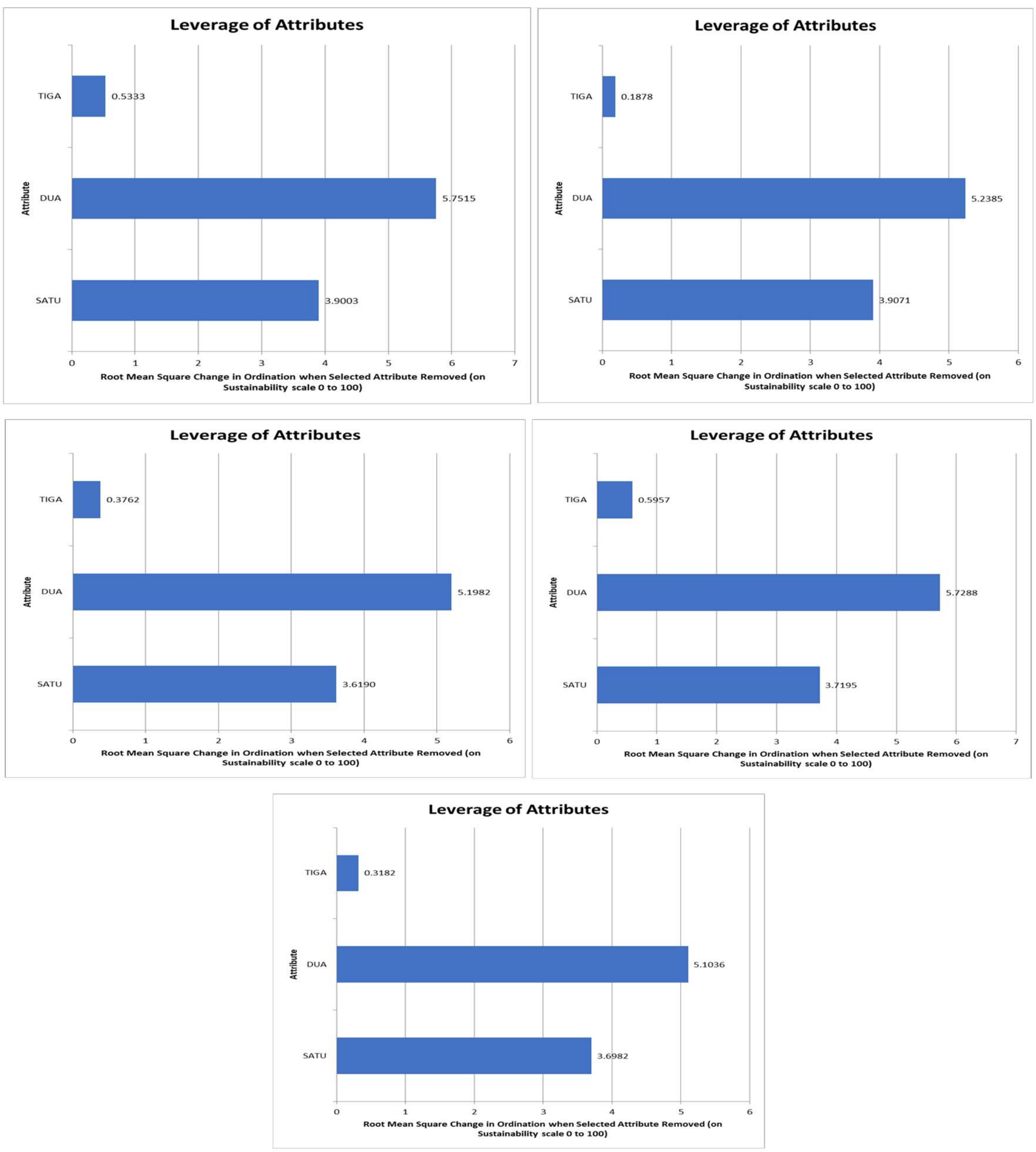

Fig. 4: Leverage Score.

The ecological dimension revealed that the most sensitive attribute was "maintenance of irrigation channels" (5.20), followed by "environmental awareness in rice farming decisions" (3.62). The presence of new rice fields as a response to industrial expansion had relatively low leverage (0.38). This highlights the importance of water infrastructure and local ecological knowledge in mitigating environmental pressures, especially those associated with sedimentation and water quality degradation. In the technological dimension, the attribute "need for organic fertilizer to restore soil fertility" held the highest leverage value (5.73), surpassing "increasing rice productivity" (3.72). The lowest leverage was attributed to "testing of new cultivation technologies to address IBA waste" (0.60). These findings suggest that addressing degraded soil conditions caused by industrial impacts is more critical than technological innovation alone, reaffirming the urgent need for restorative agricultural practices. Finally, in the institutional dimension, the highest leverage was observed in "presence of agricultural extension services" (5.10), followed by "farmer participation in farmer groups" (3.70), with "land status policy for rice fields" being the least sensitive (0.32). This underscores the pivotal role of institutions in sustainability, particularly in knowledge transfer, capacity-building and community engagement.

Overall, the leverage analysis reveals that across all dimensions, the most influential attributes tend to be internal and systemic rather than externally imposed. Profitability, youth participation, irrigation maintenance, organic soil management and extension service accessibility emerge as core sustainability drivers. These findings offer critical insights for stakeholders and policymakers, suggesting that targeted efforts toward these leverage points are likely to yield the most substantial improvements in rice farming sustainability in peri-industrial regions like Cirebon.

Monte Carlo Analysis

To assess the robustness and internal consistency of the Multidimensional Scaling (MDS) results in the RAP-Rice model, a Monte Carlo simulation was performed across all five sustainability dimensions: economic, social, ecological, technological, and institutional (Fig. 5). This analysis involved introducing random perturbations to the attribute scores and re-running the MDS configuration for three iterations. The resulting scatter plots visualize the distribution of simulated sustainability indices compared to the original (real) scores. Each scatter plot presents the real sustainability score as a green dot and the simulated scores

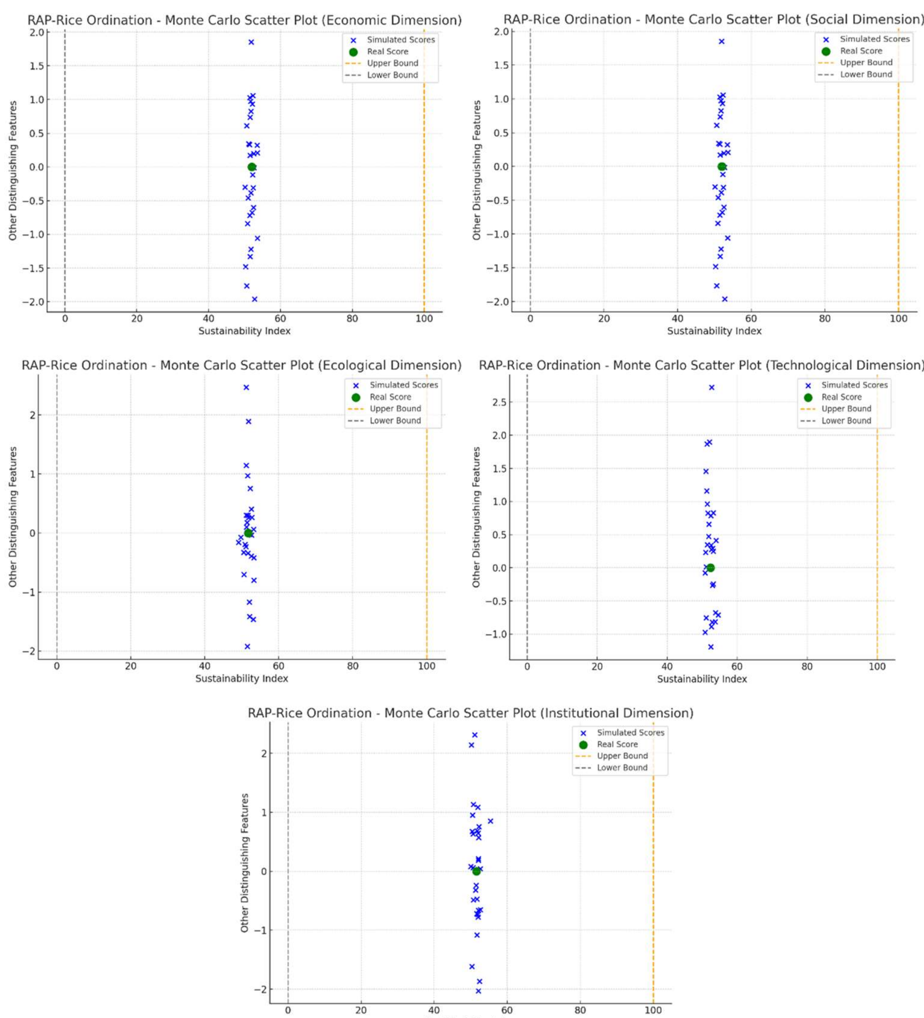

Fig. 5: Monte Carlo for Economic.

as blue X-markers. Vertical dashed lines at 0 and 100 indicate the theoretical bounds of the sustainability index scale. The Y-axis ("Other Distinguishing Features") represents the secondary dimension in the MDS ordination space. The results demonstrate a consistent pattern across all dimensions. In each plot, the simulated points are tightly clustered around the real sustainability score, forming a dense group with minimal horizontal and vertical dispersion. This indicates that the model’s outputs are stable under data variability, and that slight shifts in scoring do not significantly distort the ordination structure or sustainability classification.

In the economic dimension, the real score of 52.08 is surrounded by a concentrated cluster of simulated scores, confirming the stability of the model's assessment of profitability, input efficiency, and market access. This implies that interventions based on this dimension such as enhancing cost-efficiency or supporting pricing mechanisms are founded on a reliable sustainability estimate. Similarly, the social dimension presents a real score of 52.02 with simulated values consistently close by, indicating robustness in assessing labor dynamics, generational continuity, and social well-being. The stable configuration reinforces confidence in the interpretation that youth engagement and community cohesion are critical leverage points.

The ecological dimension, with a real score of 51.71, also shows tight clustering of simulations. Despite the inherent variability in environmental conditions, the model’s ecological assessment covering irrigation quality, soil health, and pollution exposure proves resilient. This underscores the validity of prioritizing environmental restoration and sediment management in policy responses. The technological dimension records the highest real score of 52.39, and the simulated scatter points confirm minimal variability, suggesting strong model confidence. This result affirms the importance of innovation, mechanization, and access to sustainable technologies as key components of resilience in rice farming.

Lastly, the institutional dimension, with the lowest score of 51.55, nonetheless shows a compact spread of simulated values. This suggests that while institutional support may be limited, the data measuring it are internally consistent. As such, recommendations for strengthening extension services, regulatory clarity, and farmer group participation are grounded in methodologically sound findings. Overall, the Monte Carlo simulations support the reliability of the RAP-Rice ordination across all dimensions. The low dispersion in simulated scores, combined with Stress values below 0.19 and RSQ values above 0.92 in all dimensions, confirm the robustness and precision of the model. These results validate the use of RAP-Rice as a tool for guiding targeted policy interventions in sustainability planning for rice farming systems facing industrial pressure

DISCUSSION

This study sought to (1) assess the overall sustainability status of rice farming in areas exposed to natural stone industry activities, (2) identify key leverage indicators affecting each sustainability dimension, and (3) evaluate the robustness of the RAP-Rice method in an industrial-agricultural interface context. The findings offer critical insights into how Cirebon's rice farming sector sustains itself under dual pressures from agriculture and industrialization.

Objective one is addressed through the RAP-Rice assessment, which revealed that all five sustainability dimensions, economic, social, ecological, technological, and institutional fall within the moderate category, with index values tightly clustered between 51.55 and 52.39. This narrow range illustrates a fragile balance wherein no domain is severely degraded, yet none exhibit robust resilience. This pattern reflects the concept of “marginal stability” noted in rural systems affected by land-use conflict Bergougui & Meziane (2025). These findings also support Gao et al. (2021), who advocate for multidimensional sustainability frameworks that account for interconnected socio-ecological pressures. In relation to objective two, the leverage analysis offers diagnostic clarity. The technological dimension scored the highest (52.39), indicating that farmers retain moderate access to innovation, including irrigation technologies and improved seed varieties. However, its most influential attribute was not technological sophistication but the compensatory use of organic fertilizers to counter soil degradation. This echoes the findings of Bugden (2022) and Shen & Zhang (2023), who argued that technological responses must directly address ecological deficits to be effective.

Conversely, the institutional dimension received the lowest index (51.55), highlighting systemic weaknesses in agricultural extension services, land-use policy, and enforcement. The low leverage effect of formal land tenure regulation suggests institutional mechanisms are inadequately aligned with field realities. This reinforces observations by Wang et al. (2025), who demonstrated that institutional inertia in peri-urban farming zones impedes adaptive governance. In Indonesia, similar critiques have emerged in Central Java and West Sumatra, where local governments struggle to regulate agricultural–industrial land overlap (Aminullah, 2025). The economic and social dimensions also showed moderate sustainability (52.08 and 52.02, respectively). Economic sustainability was most affected by profit efficiency, while social sustainability hinged on generational participation in farming. These attributes reflect broader trends in rural Indonesia, where youth disengagement from farming and declining margins jeopardize sectoral viability (Putri et al., 2023). The limited role of external economic assistance in improving sustainability here contrasts with more successful models in Vietnam’s Mekong Delta, where structural investments in cooperative farming have yielded higher sustainability outcomes (Nguyen, 2023). Thus, policy for Cirebon should shift from short-term subsidies to institutional frameworks that promote long-term market access, pricing stability, and inclusive agricultural education.

Ecological sustainability (51.71) was challenged by deteriorating irrigation quality and industrial runoff. The leverage analysis emphasized irrigation maintenance and farmers’ environmental concern as key factors. These results are consistent with findings in East Java, where awareness campaigns and participatory water management led to measurable gains in ecological resilience (Supiandi, 2024). Chang et al. (2024) further emphasize that sustaining rice production in industrializing regions requires ecosystem-oriented planning that integrates environmental protection with production goals. Regarding objective three, the statistical robustness of the RAP-Rice model was validated through Monte Carlo simulations, which produced negligible deviations between simulated and real scores. With Stress values below 0.19 and RSQ values exceeding 0.92, the MDS configuration demonstrated strong internal consistency and methodological reliability, confirming the analytical credibility of the findings.

In conclusion, this study contributes to the growing body of work on agricultural sustainability under industrial pressure by applying a context-sensitive, multidimensional evaluation framework. It identifies five leverage points, profitability, youth participation, environmental awareness, institutional responsiveness, and soil recovery that warrant targeted policy interventions. These findings reinforce the need for integrated approaches, where technological advances do not obscure institutional gaps and ecological priorities are not compromised by economic fragility. Future research should consider longitudinal studies to monitor temporal shifts in these indicators and explore replicability across Indonesia's other industrial-agricultural frontiers.

Implications

This study advances the theoretical application of the RAP-Rice method by demonstrating its robustness and adaptability in assessing agricultural sustainability within an industrial conflict zone. While the RAPFISH framework has been widely used in fisheries and broader agricultural settings, this research provides a methodological extension by validating its use in a rice farming context directly exposed to pollution, land-use competition, and socio-institutional vulnerabilities. The successful application of Multidimensional Scaling (MDS) with Monte Carlo simulation underlines the methodological rigor of RAP-Rice and contributes to the evolving discourse on mixed-method sustainability assessments, especially in peri-industrial landscapes.

Furthermore, the study contributes to sustainability theory by empirically illustrating how internal system attributes such as profitability, youth engagement, and institutional presence function as more critical leverage points than external policy instruments like subsidies or compensation schemes. This challenges linear policy assumptions often found in sustainable agriculture models and instead supports a systems-based perspective where multiple dimensions interact with varying sensitivities. These findings echo but also extend the multidimensional sustainability frameworks proposed by Bibri et al (2024) and Rehman et al (2024), suggesting that in regions facing industrial encroachment, internal adaptive capacity is a more reliable indicator of long-term resilience than reliance on top-down intervention. Moreover, the study yields actionable insights for policymakers, agricultural planners, and local governments seeking to sustain rice farming systems amid industrial development. First, the identification of profitability as the highest leverage attribute in the economic dimension suggests that improving farm-gate prices, reducing input costs, and facilitating stable access to markets are more impactful than one-off financial aid. This necessitates the implementation of value-chain strengthening programs tailored specifically to rice-producing zones near industrial activity.

Second, the high leverage of youth participation in farming within the social dimension points to the urgent need for intergenerational succession strategies, such as youth-targeted training, incentives for agri-preneurship, and access to land or credit. In the context of an aging farmer population, sustaining production capacity will depend on the ability to meaningfully engage younger demographics in agriculture. Third, the ecological findings emphasize infrastructure maintenance, particularly irrigation channels disrupted by sedimentation from stone processing activities. Local environmental agencies should prioritize coordinated drainage management programs and establish industry-agriculture negotiation forums to ensure shared water use without compromising paddy field integrity. Fourth, the leverage analysis in the technological dimension suggests that restorative practices, such as organic fertilization, are more effective than introducing novel technologies alone. Thus, agricultural extension services should shift focus toward soil recovery practices and low-cost ecological interventions tailored to industrially exposed soils.

Lastly, institutional improvement must go beyond generic support programs. The low institutional index and high leverage of extension service presence call for area-specific institutional strengthening, including localized capacity-building for farmer groups, clearer land tenure systems in mixed-use zones, and real-time grievance mechanisms for industrial pollution incidents. Together, these targeted interventions offer a practical roadmap for enhancing the sustainability of rice farming in Cirebon and other similar industrial-agricultural interface zones in Indonesia and beyond.

Limitation and Future Directions

While this study provides a comprehensive assessment of rice farming sustainability under industrial pressure using the RAP-Rice method, several limitations must be acknowledged.

First, the research was geographically limited to selected subdistricts within Cirebon Regency, where the natural stone industry is most concentrated. Although these areas were purposively chosen for their relevance to the research objectives, the findings may not fully represent the conditions of rice farming systems in other parts of West Java or Indonesia where industrial influences differ in scale, type, or governance structure. Future studies could adopt a comparative design across multiple regencies or provinces to evaluate spatial variation in sustainability outcomes and the scalability of the RAP-Rice framework. Second, the study relies primarily on farmer self-assessment and field observations for scoring sustainability attributes. While triangulated with secondary data and expert validation, subjective biases may still influence responses, especially in dimensions like institutional trust or perceived ecological change. Incorporating more objective biophysical measurements (e.g., soil toxicity levels, water pH, satellite imagery for land-use changes) and financial accounting data could enhance the precision of sustainability scoring in future applications.

Third, while the leverage and Monte Carlo analyses offered valuable diagnostic insights, the RAP-Rice method remains a rapid appraisal tool that does not model causal relationships or longitudinal change. Future research should complement RAP-Rice with more dynamic modeling approaches such as system dynamics, agent-based modeling, or structural equation modeling to capture temporal changes and feedback loops among sustainability dimensions. Lastly, the current study did not incorporate stakeholder perspectives beyond the farming community, such as local industry representatives, environmental agencies, or village leaders. Given the complexity of industrial-agricultural interactions, future research should adopt a more inclusive multi-stakeholder approach to sustainability assessment, ensuring that proposed interventions reflect both farmer needs and institutional realities. By addressing these limitations, future research can build on this study's contributions to develop more granular, scalable, and participatory sustainability strategies for agriculture in contested rural landscapes.

Conclusion

This study evaluated the sustainability of rice farming systems in Cirebon District, Indonesia, using the RAP-Rice method to account for economic, social, ecological, technological, and institutional dimensions. All five dimensions exhibited moderate sustainability, with key leverage indicators including profitability, youth participation, irrigation infrastructure, soil recovery efforts, and agricultural extension support. The findings suggest that policy interventions should prioritize strengthening institutional responsiveness, promoting intergenerational farming engagement, and supporting ecological restoration practices to maintain agricultural viability in industrializing regions. These multidimensional insights are crucial for designing integrated strategies that safeguard food systems under land-use pressures. Future research should extend this analysis through longitudinal designs or cross-regional comparisons to capture dynamic sustainability trajectories and test the scalability of targeted interventions.

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Data Availability: Data will be available at request

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Consent to Participate: All participants involved in this study provided informed consent prior to data collection. Respondents were assured of the confidentiality and anonymity of their responses, and participation was voluntary.

Consent to Publish: The authors affirm that all participants were informed that the aggregated and anonymized results would be published in academic outlets. Consent to publish these findings was obtained in accordance with ethical research practices.

Author's Contribution: S.W. conceptualized the research framework and led the RAP-Rice sustainability analysis. L.S. supervised the research design and provided oversight on methodology. I.S. contributed to data collection and the validation of ecological indicators. E.W. performed statistical analyses and drafted sections of the manuscript. All authors (S.W., L.S., I.S., and E.W.) contributed to reviewing, editing, and approving the final version of the manuscript.

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