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Anthropogenic Processes and Ecosystem Functioning in Post-Mining Landscapes: The Role of Employee Behavior

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ABSTRACT

Ecosystem recovery in post-mining landscapes represents a complex process shaped by dynamic interactions between biophysical dynamics and sustained anthropogenic inputs. This study examines employee ecological behavior as a functional anthropogenic factor influencing ecosystem functioning in a tropical post-mining landscape in East Kalimantan, Indonesia. Using an integrated empirical approach combining behavioral survey data from 136 mining employees with long-term ecosystem performance records of mining companies, we evaluate how sustained human-mediated actions relate to vegetation recovery, carbon sequestration, and landscape stabilization. Results indicate that while technical ecological knowledge among employees is moderate (mean score 3.2/5.0), the stability and continuity of employee pro-environmental behaviors show strong positive associations with measurable ecosystem recovery outcomes, including extensive land reclamation (1,875 ha over five years), increased vegetation cover (2.25

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million trees planted), and significant carbon sequestration (33,800 tCO_2e annually). These findings suggest that repeated employee interventions, when sustained over time and embedded within supportive organizational systems, may operate as cumulative anthropogenic processes contributing to recovery trajectories in degraded landscapes. However, we acknowledge that current data cannot isolate the independent causal effect of employee behavior from other organizational factors, including capital investment, technological infrastructure, and management systems. By conceptualizing employee behavior as an embedded anthropogenic factor rather than an external social variable, this study contributes to applied ecology by proposing a conceptual framework for understanding how employee actions may contribute to ecosystem functioning in post-mining contexts. The mechanistic pathways proposed require further validation through integrated social-ecological research designs.

Keywords: Anthropogenic Processes; Ecosystem Functioning; Post-Mining Ecosystems; Ecological Restoration; Vegetation Recovery; Carbon Cycling

1. Introduction

Coal mining remains one of the most ecologically challenging extractive industries worldwide, generating substantial environmental pressures through land degradation, biodiversity loss, hydrological disruption, and greenhouse gas emissions [1]. The global transition toward sustainable development has intensified demands on industries to internalize ecological principles and to minimize anthropogenic impacts on ecosystems. Within this context, sustainability in the mining sector is increasingly examined through the lens of applied ecology, where human behavior, organizational systems, and ecological processes are interconnected within complex social–ecological systems [2,3].

The degradation of ecosystems caused by mining underscores the necessity to understand and manage interactions between the social and ecological subsystems that determine ecological resilience. Recent frameworks such as the planetary boundaries concept have emphasized that human economic activity has already exceeded several safe operating limits for Earth's systems, especially those associated with climate regulation, biogeochemical cycles, and land-use change [4].

In ecological science [5–7], ecosystem functioning refers to the capacity of ecosystems to sustain fundamental biophysical processes such as primary productivity, nutrient cycling, energy flow, and biomass accumulation that collectively determine ecosystem services and resilience. Extensive ecological research has demonstrated that changes in biotic composition and process regulation directly alter ecosystem functioning across spatial and temporal scales, particularly in disturbed landscapes. In post-mining environments, ecosystem functioning is therefore not only a biophysical outcome, but a dynamic process shaped by interacting ecological and anthropogenic pathways. Ecosystem functioning is traditionally understood as the capacity of ecological systems to sustain fundamental processes such as primary production, nutrient cycling, and energy flows, which underpin ecosystem services and resilience [5–7]. Consequently, industries are now urged to not only comply with environmental regulations but to embed ecological reasoning into their core management and operational cultures [8]. This has shifted the focus of sustainability research from purely technological and financial pathways to include human behavioral and organizational factors that influence ecological outcomes [9,10].

In extractive industries, corporate environmental responsibility (CER) programs have been widely adopted to balance economic growth with ecological protection and community welfare [11,12]. These programs aim to transform corporate behavior by promoting environmental stewardship and ensuring long-term ecosystem functioning in mining landscapes. However, the success of CER initiatives depends not only on managerial commitment or regulatory compliance but also on the ecological awareness, knowledge, and everyday actions of employees. As the individuals most directly involved in operational activities, employees play a decisive role in translating corporate environmental policies into tangible ecological outcomes [13,14].

Evidence from empirical research suggests that employees' engagement in pro-environmental behavior has measurable ecological impacts, including improved energy efficiency, reduced waste generation, and increased effectiveness of reclamation projects [10,15]. Within the workplace, pro-environmental behavior is often driven by a combination of knowledge, awareness, motivation, and perceived organizational support. When these factors align with an organization's sustainability culture, they can reinforce collective ecological performance. Nonetheless, the persistence of knowledge behavior gaps the discrepancy between environmental awareness and actual behavioral change remains a challenge across many industrial sectors [13]. Overcoming this gap requires integrating behavioral ecology perspectives into sustainability management, viewing humans not merely as resource users but as active ecological agents within their organizational ecosystems.

The mining sector has been undergoing a gradual transition toward eco-efficient systems integrating resource efficiency, emission reduction, and ecological restoration within production processes in contemporary times. This approach resonates with the goals of applied ecology by promoting the restoration of ecosystem functions such as soil regeneration, hydrological balance, and biodiversity maintenance in post-mining landscapes [16]. Studies have shown that companies that successfully integrate sustainability into their operations often foster strong internal cultures of environmental responsibility, where employees perceive themselves as contributors to ecological protection rather than merely industrial laborers [12,17].

Nevertheless, despite the growing body of research linking CSR or CER to environmental outcomes, most studies remain externally focused on analyzing community impacts, corporate reputation, or stakeholder trust [18]. A restricted quantity of scholarly works has investigated the internal ecological dimension of sustainability, particularly how employees' perceptions, environmental knowledge, and well-being contribute to ecosystem functioning within industrial organizations. This lack of internal focus constrains our understanding of how corporate environmental responsibility operates through human-mediated pathways. In applied ecological terms, this constitutes a critical research gap: understanding the behavioral and perceptual pathways that connect organizational structures to ecosystem-level effects [2,19].

Moreover, while workplace environmental behavior has been examined in sectors such as manufacturing and services [10], the context of large-scale mining with its extensive ecological footprint remains underrepresented in ecological and sustainability research. The mining industry is unique because its operations directly alter physical landscapes and biotic communities, making it a crucial site for studying how human behavior can influence ecological restoration processes. Employees' ecological knowledge and awareness are thus not only social assets but also ecological determinants, shaping the success of reclamation, reforestation, and biodiversity conservation efforts.

In tropical developing regions such as Southeast Asia, coal mining often overlaps with biodiversity-rich ecosystems, amplifying both the risks and opportunities of sustainable management. In Indonesia, for instance, mining companies are required by regulation to conduct post-mining reclamation and environmental rehabilitation, yet the quality and long-term ecological success of such efforts depend on human participation and compliance within organizations. Mining regions such as East Kalimantan have become focal points for implementing integrated social–ecological management, where ecological restoration is supported by corporate sustainability programs and community engagement. Such settings provide an ideal empirical context for examining the human dimensions of ecological functioning in mining systems.

From an applied ecology standpoint, employees can be conceptualized as micro-level ecological actors embedded within a broader industrial ecosystem. Their behaviors range from waste management and energy use to participation in environmental campaigns, and represent micro-scale ecological processes that collectively influence macro-scale outcomes such as habitat recovery and carbon sequestration. Tam [20] proposed that promoting pro-environmental behavior requires understanding the psychological, cultural, and contextual factors that drive individual decisions within institutional environments. Therefore, employees' ecological perception, awareness, and well-being must be analyzed not as isolated social indicators but as integral components of ecosystem governance.

A growing body of literature supports the notion that ecological sustainability in industries is achieved through the co-evolution of social and natural systems [3,8]. This co-evolutionary perspective recognizes that organizations and ecosystems are adaptive systems that continuously influence each other through feedback pathways. In mining, this interaction manifests in how corporate practices affect soil quality, water systems, and biodiversity, and conversely, how ecological conditions shape corporate responsibilities and employees. By conceptualizing corporate sustainability as a dynamic feedback system between humans and nature, applied ecology provides a powerful framework to analyze the behavioral and ecological pathways that lead to resilient socio-ecological outcomes [2].

This study builds upon this conceptual foundation by examining the interplay between employees' ecological perception, awareness, pro-environmental behavior, and wellbeing, and their implications for ecosystem functioning within sustainable mining practices. Specifically, it investigates how the social dimensions of corporate environmental responsibility translate into ecological performance through human behavior in the workplace. The research employs a mixed-methodological framework that integrates qualitative and quantitative survey instruments to analyze these relationships within a major coal mining context in Southeast Asia.

By integrating social and ecological perspectives, this research seeks to advance the understanding of human ecosystem linkages in industrial environments. It addresses key questions about how employees' environmental attitudes and behaviors contribute to the ecological functioning of post-mining landscapes, and how organizational culture can serve as an ecological driver. The results are anticipated to yield contributions to both practical applications and theoretical frameworks. Theoretically, by expanding the applied ecology framework to incorporate behavioral dimensions; and practically, by informing sustainability management strategies that enhance ecological outcomes through human engagement.

In summary, this study positions itself within the broader discourse of ecological sustainability by emphasizing the role of human behavior in maintaining ecosystem functioning under industrial conditions. It argues that ecological restoration and conservation efforts in mining enterprises depend not only on technological and financial investment but also on the extent to which employees internalize ecological values and enact them in their daily work practices. In this study, anthropogenic processes are explicitly defined as sustained, human-mediated ecological actions embedded within industrial operations, through which repeated interventions such as reclamation, revegetation, and resource regulation function as active pathways of ecosystem functioning in post-mining landscapes. Therefore, the particular objectives of the present investigation are threefold: (1) to analyze employees' perceptions of corporate environmental responsibility, (2) to assess their levels of ecological knowledge, awareness, pro-environmental behavior, and well-being, and (3) to explore the interrelationships among these variables in relation to ecosystem functioning within sustainable mining operations. By doing so, the research enhances applied ecological knowledge and provides practical insights into ecological applications of how human behavior serves as a key pathway linking corporate governance and ecosystem resilience.

From an applied ecology perspective, employees are conceptualized in this study as anthropogenic ecological agents embedded within an industrial social ecological system. Their routine behaviors, such as participation in reclamation, energy conservation, waste management, and biodiversity protection, constitute micro-scale ecological processes that cumulatively influence macro-scale ecosystem functions. Rather than treating human behavior solely as an external disturbance, this research frames employees' ecological behavior as a functional driver that modulates ecosystem recovery trajectories in post-mining landscapes. This framing allows human behavioral dynamics to be analyzed alongside ecological processes such as vegetation recovery, carbon cycling, and landscape stabilization.

2. Materials and Methods

This research adopted a mixed-methods approach to comprehensively analyze employees' ecological perceptions, knowledge, awareness, pro-environmental behavior, and well-being within the context of sustainable mining operations. The methodological approach combined quantitative and qualitative techniques to capture both measurable patterns and contextual meanings behind employees' ecological attitudes and actions. This dual approach enabled methodological triangulation and strengthened the validity and robustness of the results, in line with established practices in applied ecology, ecological psychology, and environmental management research [21,22].

2.1. Research Design

The mixed-methods framework consisted of two interlinked phases. The first phase was a quantitative survey designed to assess employees' perceptions and ecological behaviors using standardized instruments adapted from validated scales in previous environmental behavior research. The second phase comprised qualitative interviews and documentary analysis, which aimed to explore the underlying social and organizational pathways influencing ecological engagement in the workplace. This explanatory sequential model allowed quantitative results to guide qualitative inquiry, thereby integrating numerical trends with narrative insights.

The rationale for adopting a mixed-methods approach was based on the recognition that ecological behavior is a multidimensional construct involving psychological, cultural, and organizational factors. While quantitative data captures general tendencies, qualitative evidence provides nuanced understanding of contextual pathways such as corporate culture, leadership, and institutional norms. The integration of both forms of data strengthened interpretive validity and enhanced the generalizability of conclusions.

2.2. Study Site and Participants

The study was conducted within a large-scale coal mining enterprise operating in East Kalimantan, Indonesia, a region characterized by extensive tropical ecosystems and a long history of mining-related environmental transformation. The company's concession area covers approximately 61,500 ha, with both active extraction sites and post-mining reclamation zones. The research setting included the company's central administration, mining operations in Sangatta and Bengalon, and supporting facilities such as environmental laboratories, training centers, and reclamation sites [23,24].

The target population consisted of the company's 3,751 permanent employees and approximately 29,600 contract personnel. The final sample size of 136 employees was determined using proportional random sampling to ensure representation from key divisions: mining operations, Environment, Human Resources, and Community Development. The inclusion criteria stipulated that participants must have a minimum of 2 years of service and direct or indirect involvement in environmental programs.

2.3. Data Sources and Availability

Three categories of data were utilized:

1. Using surveys and semi-structured interviews, primary data were obtained from employees and managers.
2. Secondary data, extracted from the company’s Sustainability Reports (2022–2023) [23,24], internal Environmental Management System documentation, and environmental performance reports.
3. Supplementary open materials, including national environmental regulations and regional reclamation statistics, were used to contextualize findings.

All anonymized datasets, survey questionnaires, interview guides, and requests for the coding matrices should be directed to the corresponding author and are subject to confidentiality review. No proprietary software or restricted databases were used in data analysis.

2.4. Instruments and Measurement Scales

The quantitative survey instrument was structured around five primary constructs, each measured on a five-point Likert scale (5 = strongly agree to 1 = strongly disagree):

1. Corporate Environmental Responsibility (CER) was adapted from Schaefer et al. [12] to evaluate perceptions of environmental and social responsibility.
2. Environmental Knowledge was adapted from Miah et al. [14] to assess respondents' understanding of ecological concepts and practices.
3. Ecological Awareness was based on Novotný et al. [18], measuring individual concern for environmental issues and sustainability values.
4. Environmental Behavior was derived from Alrifae [25], capturing self-reported ecological actions at the workplace such as waste sorting, energy conserva-

tion, and participation in reforestation.

5. Employees were adapted from Pratiwi et al. [17], reflecting the physical, psychological, and social dimensions of workplace well-being.

Prior to full implementation, the questionnaire was pilot tested with 30 participants to assess its validity and clarity. Item total correlations exceeded 0.30 for all items, and coefficients of Cronbach's alpha for the five scales ranged between 0.78 and 0.91, confirming internal reliability [26]. Construct validity was confirmed through factor analysis, which yielded loadings above 0.50 on their intended dimensions.

The qualitative interview protocol consisted of open-ended questions addressing perceptions of environmental responsibility, experiences with ecological programs, and reflections on company culture. Five key informants were interviewed: the Environmental Manager, Head of Human Resources, Head of Community Development, and two field supervisors from operational units. In Indonesian, the interviews were carried out, audio-recorded with participant consent, and transcribed verbatim.

2.5. Data Collection Procedures

Data collection was carried out between January and April 2025 in three stages.

1. Quantitative survey: The survey was administered online using a secure Google Form platform. Participation was entirely voluntary, and informed consent was secured from all respondents. Respondents were assured anonymity, and no personally identifiable information was collected.
2. Qualitative interviews: Semi-structured interviews were held face-to-face and via online platforms for remote participants. Each session lasted approximately 45–60 min. The interviews explored employees' understanding of environmental responsibility, participation in ecological initiatives, and perceived barriers to sustainable behavior.
3. Documentary review: Sustainability and environmental management reports for 2022–2023 were systematically examined to verify claims regarding reclamation areas, emission reduction, biodiversity protection, and employee participation. These documents were coded to align with the thematic categories identified from interviews, facilitating cross-validation of data sources.

All procedures complied with ethical standards for human-subjects research as stipulated by the institutional ethics committee. Respondents were voluntary and retained the right to withdraw at any stage without consequence.

2.6. Data Analysis

Quantitative analysis was conducted using frequencies, descriptive statistics, means, and fractions to determine the levels of perception, knowledge, awareness, pro-environmental behavior, and well-being. Mean scores were interpreted using the following intervals: 4.21–5.00 (very high), 3.41–4.20 (high), 2.61–3.40 (moderate), 1.81–2.60 (low), and 1.00–1.80 (very low).

Correlation and cross-tabulation analyses were additionally performed to examine relationships among the five variables. Statistical analysis was executed using SPSS v26 (IBM Corp, USA). All analysis scripts and outputs are available upon request in open-text format to ensure reproducibility.

Qualitative analysis followed the thematic analysis approach proposed by Braun and Clarke [27]. The process involved six stages: data familiarization, initial data classification, emerging theme, validation, clarification, and reporting.

Two researchers independently coded the transcripts using NVivo 12 software, with intercoder agreement exceeding 0.85 (Cohen's kappa). Emerging themes included “ecological awareness,” “sustainability culture,” “organizational support,” and “workplace ecological behavior.” The integration of quantitative and qualitative findings was achieved through a triangulation protocol, aligning statistical results with thematic insights to produce a coherent interpretation.

3. Results

3.1. Participant Demographics

An overall total of 136 employees participated in the survey. The majority were male (80.1%), representing the gender composition typical of the mining sector. Most respondents were within the 41–60 years age group (67.6%) and held undergraduate degrees (55.9%), indicating a relatively well-educated and experienced workforce.

Over half of the participants had 11–20 years of work experience (59.6%), reflecting a high level of professional engagement and familiarity with the company's operational and environmental management systems. This demographic structure provides a reliable foundation for evaluating employees' perceptions of the company's environmental and social responsibility policies.

3.2. Descriptive Results of Research Variable

Table 1 presents the descriptive statistics for the five main variables investigated in this study.

Table 1. Descriptive Results of Key Study Variables.

Variable	Mean	Category	Interpretation
Corporate Environmental Responsibility (CER)	4.57	Very High	Company consistently implements integrated environmental–social policies
Environmental Knowledge	2.93	Moderate	Limited technical understanding of ecological systems and environmental indicators
Environmental Awareness	4.32	Very High	Employees demonstrate strong awareness of conservation and resource efficiency
Environmental Behavior	4.41	High	Employees actively engage in energy saving and waste management
Employees' Well-being	3.75	High	Stable physical and psychological well-being support ecological participation

Source: Primary data (2025).

The results indicate very high levels of perceived corporate environmental responsibility and environmental awareness among employees, along with high environmental behavior and well-being. However, the moderate score for environmental knowledge suggests a partial disconnect between awareness and technical understanding, a pattern consistent with the “knowledge behavior gap” identified in previous environmental psychology research [22].

3.3. Perceptions of Corporate Environmental Responsibility

Employees' perceptions of corporate environmental responsibility were very high (mean = 4.57). Respondents consistently viewed the company as demonstrating strong commitment to environmental protection and social welfare through integrated sustainability initiatives. Secondary data corroborate these perceptions: the company's 2022 Sustainability Report recorded USD 66.6 million in environmental management investments, 1,917 ha of land reclamation, and the planting of 885,000 trees. In 2023, reclamation areas expanded to 14,608 ha, equivalent to 39.9% of the total active operational area.

Flagship environmental programs such as the Pond Configuration Smart Solution and Agro-Energy Plantation Trials exemplify initiatives that directly support ecosystem functioning, including carbon sequestration, soil stability, and biodiversity restoration. As one environmental manager explained:

> *"Employees' participation in reforestation, waste management, and water conservation is essential. Their awareness ensures that environmental policies are implemented effectively in the field."* (Interview, Environmental Manager, 2025)

These findings demonstrate how corporate environmental responsibility translates into ecological outcomes through active employee involvement, reinforcing the interdependence between social engagement and ecological performance in applied ecology.

3.4. Environmental Knowledge and Awareness

The results reveal a distinct contrast between high environmental awareness (mean = 4.32) and moderate environmental knowledge (mean = 2.93). While most employees express strong concern for environmental protection, their technical understanding of ecological concepts such as carbon cycles, biodiversity indices, or hazardous waste management remains limited.

This pattern illustrates the classic knowledge behavior gap [22], wherein high awareness does not necessarily correspond to in-depth ecological literacy. Nevertheless, awareness still serves as a key precursor to sustainability-oriented behavior, fostering a "sustainability culture" within the organization.

The company has introduced various environmental literacy programs, including the Green Office Movement, waste management training, and Environmental and energy management certifications under ISO 14001 and ISO 50001. However, interviews with supervisors suggest that such programs are not yet uniformly distributed across all departments, explaining the relatively moderate level of environmental knowledge.

Despite this limitation, employees' awareness levels indicate a mature understanding of ecological responsibility, aligning with current applied ecology frameworks that emphasize the role of human awareness in reinforcing ecosystem resilience [2].

3.5. Environmental Behavior at the Workplace

The mean score of 4.41 reflects a high level of ecological engagement among employees. The most frequently reported behaviors include:

- Reducing electricity and water consumption in work areas (92.6% of respondents).
- Sorting waste and supporting zero-waste office initiatives (88.2%).
- Participating in Eco Day and reforestation campaigns (73.5%).

Statistical analysis confirms a strong, positive correlation between perceptual variables of environmental responsibility and environmental behavior ($r = 0.68$, $p < 0.01$). This indicates that individuals who have greater confidence in their company's environmental integrity are more inclined to participate in ecological practices.

The ecological impact of such behaviors is reflected in the company's 2023 Sustainability Report, which documents annual carbon sequestration of 289,772 t CO_2eq and an increase in vegetation cover to 48% in active reclamation areas. These outcomes indicate a functional linkage between individual-level ecological behavior and ecosystem recovery processes at the organizational scale.

Thus, employees' environmental behavior can be understood not as symbolic compliance but as a functional component of ecosystem recovery, demonstrating that human behavior within corporate systems plays an active role in maintaining ecological processes, a central principle of applied ecology.

3.6. Employees' Well-being and Ecological Engagement

The overall mean score for employees (3.75) indicates a high level of job satisfaction and psychological stability, which serve as enablers for ecological engagement. Welfare initiatives such as the Health and Safety Initiative, Apprentice Mechanic Program, and health insurance support (BPJS Kesehatan) contribute to employees' sense of belonging and organizational commitment.

According to the social ecological systems theory, social stability and well-being are foundational for ecological sustainability [28]. Employees who perceive high well-being tend to exhibit greater intrinsic motivation for environmental participation, fostering reciprocity between human and ecological well-being.

One operational employee stated:

> *"We feel proud to be part of the reforestation and rehabilitation process. It makes us part of the solution, not the problem."* (Interview, Operations Staff, 2024)

This sense of moral satisfaction underscores that ecological participation in the workplace contributes not only to environmental outcomes but also to employees' psychosocial fulfillment, reinforcing the feedback loops between well-being and ecological behavior.

3.7. Human Mediated Anthropogenic Processes as Pathways of Ecosystem Functioning in Post-Mining Landscapes

In anthropogenically transformed landscapes, human actors constitute persistent ecological forces shaping ecosystem structure and function [28,29]. The framework conceptualizes employees as anthropogenic ecological agents embedded within an industrial social ecological system. Institutional pathways (corporate environmental responsibility) and individual-level conditions (ecological awareness, ecological knowledge, and well-being) shape employees' ecological behavior, which operates as a mediating ecological process. Through routine actions such as energy conservation, waste management, reclamation participation, and biodiversity supporting practices, human behavior directly influences ecosystem recovery processes, including vegetation regeneration, carbon sequestration, soil stabilization, and biodiversity restoration. Dashed arrows indicate feedback pathways whereby improving ecosystem conditions, reinforcing organizational commitment and ecological awareness, highlight the co-evolution of social and ecological components in post-mining systems.

Contemporary ecology increasingly recognizes that many ecosystems are human-dominated systems in which anthropogenic processes operate alongside biophysical dynamics. In such systems, human actors represent persistent ecological forces that modify disturbance regimes, material flows, and recovery trajectories. This perspective is particularly relevant in post-mining landscapes, which are widely characterized as novel or anthropogenically transformed ecosystems where ecosystem functioning emerges from the interaction between human management and ecological processes [29,30].

The empirical findings align with the conceptual framework illustrating hypothesized linkages presented in **Figure 1**, which positions employees' ecological behavior as a mediating ecological process linking anthropogenic pathways to ecosystem functioning in post-mining landscapes. High levels of perceived corporate environmental responsibility, ecological awareness, and employees' well-being represent key anthropogenic pathways within the industrial social–ecological system. These pathways collectively shape employees' ecological behavior, which operates as a proximal pathway translating institutional commitment into ecological outcomes.

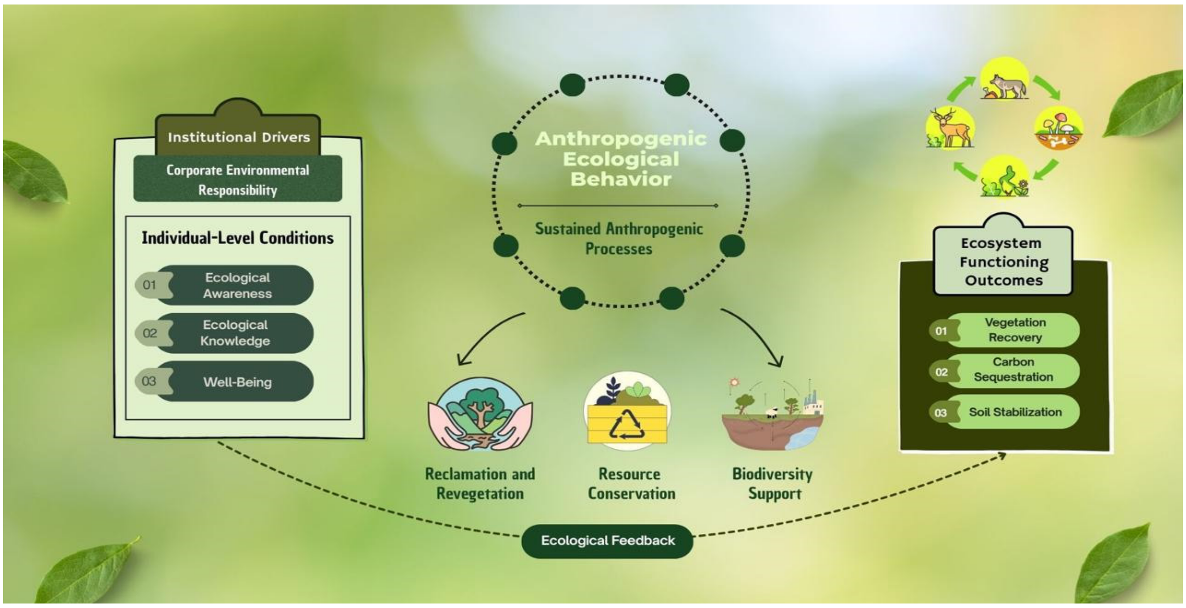

Figure 1. Conceptual framework illustrates hypothesized linkages between employees' ecological behavior as an anthropogenic pathway of ecosystem functioning in post-mining landscapes.

As illustrated in **Figure 1**, employees' ecological behavior functions as an anthropogenic ecological process rather than a purely social attribute. Survey results demonstrate high engagement in energy conservation, waste and material flow management, and participation in reclamation and revegetation activities. These routine actions constitute repeated, small-scale human interventions that cumulatively influence ecological processes at the landscape level. The association between strong perceptions of corporate environmental responsibility and elevated pro-environmental behavior confirms the left-to-center linkage in **Figure 1**, where institutional and individual pathways activate ecological behavior.

Documented environmental performance data further substantiates the center-to-right pathway of the framework. Reclaimed land area expansion, increased vegetation cover, carbon sequestration gains, and biodiversity-supporting initiatives represent ecosystem recovery outcomes that correspond to sustained human-mediated ecological processes. While these ecological indicators are reported at the organizational scale, their realization depends on consistent behavioral engagement at the operational level, reinforcing the conceptualization of employees as functional ecological agents within post-mining systems.

These results support the applied ecology principle that micro-level human behavior influences macro-level ecological stability [16,31]. Within industrial ecosystems, employees act as ecological agents whose cumulative actions, such as conserving resources or rehabilitating degraded land, contribute directly to broader ecosystem functioning through vegetation recovery, erosion control, and carbon reduction. Hence, mining corporations function not only as economic entities, but also as ecological actors embedded within the social–ecological systems they transform.

4. Discussion

The discussion interprets the findings using the applied ecological framework presented in **Figure 1**, which conceptualizes employees' ecological behavior as an anthropogenic process embedded within ecosystem functioning. The results support applied ecological perspectives that ecosystem dynamics in anthropogenically transformed landscapes are shaped not only by biophysical conditions but also by sustained human-mediated processes [31,32].

4.1. Behavioral Dimensions of Ecosystem Functioning

It is critical to acknowledge that this study documents associations between employee environmental behavior and corporate environmental performance but does not establish direct causal proof that employee behaviors independently drive ecosystem recovery. The observed improvements in ecological metrics, including 1,875 ha reclaimed, 2.25 million trees planted, and substantial carbon sequestration, may result from multiple factors, including capital investment, technological advancement, management systems, policy implementation, and employee behavior operating in concert. Our conceptual framework proposes employee behavior as one contributing factor within a complex social-ecological system, but the current data cannot isolate or quantify its specific independent contribution. Further research employing integrated social-ecological monitoring, experimental designs, and longitudinal tracking is needed to verify the specific causal pathways through which employee actions translate to measurable ecosystem outcomes. The associations documented here provide an important foundation, but mechanistic validation remains a priority for future work.

High levels of employee engagement in ecological behavior indicate that routine human actions operate as functional components of ecosystem processes in post-mining landscapes. Activities such as energy conservation, waste segregation, and participation in revegetation constitute repeated, small-scale interventions that cumulatively influence ecosystem functions, including vegetation recovery and carbon sequestration. Similar patterns have been identified in applied ecological studies emphasizing the role of employees in restoring degraded ecosystems, Pouresmaieli et al. [16] and Islam et al. [19], who argue that behavioral ecology within organizations is critical to restoring ecosystem functions in post-mining landscapes.

From an ecological perspective, these behaviors contribute to the re-establishment of key ecosystem functions such as biomass accumulation, nutrient cycling, and primary productivity. Rather than acting as isolated social practices, employees' behaviors function as scaling pathways through which micro-level actions generate landscape-level ecological outcomes. This finding aligns with ecological theory highlighting how sustained small-scale processes can produce emergent ecosystem patterns over time. The observed knowledge-behavior gap, where moderate ecological knowledge coexists with high ecological engagement, suggests that direct ecological outcomes are not solely dependent on technical understanding. Instead, consistent behavioral implementation appears sufficient to influence ecosystem functioning, particularly when supported by organizational structures. This finding reinforces applied ecology arguments that functional outcomes can precede comprehensive ecological literacy in managed ecosystems.

In this study, employees' energy conservation, waste segregation, and reforestation activities represent micro-level ecological processes that collectively generate macro-level effects such as increased vegetation cover and carbon sequestration. These employees contribute to the re-establishment of essential ecosystem functions such as nutrient cycling and primary productivity, thus reinforcing the organization's ecological resilience [13,14]. Consequently, corporate training and communication strategies should aim to strengthen technical ecological literacy while maintaining motivational and value-based engagement.

4.2. Organizational Structure and Human Stability as Enabling Ecological Processes

Within anthropogenically transformed ecosystems, ecosystem functioning depends not only on biophysical conditions but also on the stability and regulation of anthropogenic processes. In post-mining landscapes, organizational structures function as ecological regulators by shaping the consistency, intensity, and spatial distribution of human-mediated interventions such as reclamation, revegetation, and resource management.

In this study, strong institutional commitment to environmental responsibility provides a stable governance framework that reduces variability in human behavior and ensures the persistence of ecological interventions over time. From an applied ecology perspective, such organizational stability operates analogously to ecological controls in natural systems, regulating disturbance regimes and facilitating predictable recovery trajectories.

Organizational structures shape the intensity and consistency of anthropogenic ecological processes within industrial ecosystems. In this study, strong institutional commitment to environmental responsibility provides a stable governance framework that regulates human-mediated ecological interventions. Such structures function analogously to ecological controls, influencing disturbance regimes, resource flows, and recovery trajectories. The role of organizational culture emerged as a central driver of ecological engagement. The company's internal motto was "More Than Mining," which functions as a shared narrative that aligns individual identity with environmental stewardship. This finding resonates with the concept of the sustainability mindset proposed by Williams and Schaefer [9], which emphasizes how values embedded within corporate culture foster long-term ecological responsibility.

Rather than emphasizing cultural narratives, the ecological significance lies in how organizational systems standardize and reproduce behaviors that affect ecosystem processes. Comparable findings in extractive industries indicate that consistent institutional frameworks enhance the effectiveness of reclamation and restoration efforts by stabilizing human inputs over time [12,15].

Employees' well-being further supports ecosystem functioning by stabilizing human participation in restoration processes. Stable physical and psychological conditions reduce fluctuations in anthropogenic inputs, thereby sustaining continuous ecological actions essential for vegetation establishment, soil stabilization, and carbon accumulation. Within social ecological systems theory, this stability enhances system resilience by maintaining the functional capacity of employees to contribute to ecosystem processes.

Employees' well-being emerges as an enabling condition that supports the continuity of anthropogenic ecological processes. Stable physical and psychological conditions reduce behavioral variability and support sustained engagement in ecological practices. Within social–ecological systems theory, such stability enhances system resilience by maintaining the capacity of human agents to participate in ecosystem management [2,28].

Rather than functioning as a social outcome, well-being operates ecologically by stabilizing employees' contributions to restoration processes. When well-being is maintained, anthropogenic ecological inputs such as participation in reclamation or conservation activities remain consistent, reinforcing ecosystem recovery trajectories. This finding supports applied ecology perspectives that human system stability underpins long-term ecosystem functioning in managed landscapes [3].

4.3. Data Chain Gap and Study Limitations

A critical limitation of this study is the absence of direct, empirically measured links between specific employee behaviors and discrete ecological outcomes at the plot or unit level. While we documented strong associations between employee environmental attitudes, self-reported behaviors, and aggregate corporate environmental performance metrics, the current study design cannot isolate the independent causal contribution of employee behavior from other factors, including capital investment, technological infrastructure, and management systems.

The company's overall environmental performance, including total area reclaimed, carbon sequestered, and vegetation cover, was represented as a composite outcome influenced by multiple interacting factors. Our behavioral survey data and corporate performance reports exist at different scales and lack the spatial and temporal resolution needed to establish direct cause-and-effect relationships. This represents a significant 'data chain gap' in the evidence base.

Employee environmental behavior operates within a complex organizational system where technological capabilities, financial resources, management directives, regulatory requirements, and infrastructure all shape ecological outcomes. While our data demonstrate a strong positive association between employee engagement in pro-environmental behaviors and corporate environmental performance, we cannot quantitatively partition the variance attributable to employee actions versus these other factors. The observed ecosystem recovery may result from synergistic interactions among all these elements rather than from employee behavior alone.

Furthermore, our reliance on self-reported behavioral data introduces potential social desirability bias, where employees may overreport pro-environmental behaviors. The aggregate nature of corporate environmental reports also prevents fine-grained analysis of how specific employee actions (e.g., planting specific tree species, implementing soil management techniques) translate to measurable ecological responses in specific locations over defined time periods.

Future research should integrate:

(1) Pot-level ecological monitoring with known employee activity assignments, allowing direct spatial correlation between actions and outcomes;

(2) Remote sensing data with temporal resolution matching behavioral interventions;

(3) Quasi-experimental designs comparing areas with different levels of employee engagement while controlling for other factors;

(4) Longitudinal tracking systems that link individual or team actions to measurable ecological responses over time;

(5) Qualitative case studies documenting the pathways through which employee behaviors translate to ecological outcomes.

Therefore, our primary contribution should be understood as: (a) revealing strong associations between positive environmental culture and overall environmental performance in a post-mining context, and (b) proposing an innovative conceptual framework for understanding the potential role of employee behavior as one factor within complex ecosystem recovery processes. The mechanistic pathways proposed in our conceptual model require further empirical validation through integrated social-ecological research designs that can overcome the data chain gap identified in this study.

4.4. Employees' Ecological Behavior as an Anthropogenic Pathway of Ecosystem Functioning

To translate the conceptual relationships depicted in **Figure 1** into testable ecological pathways, **Figure 2** presents a concept-to-metrics framework that links employees, mediated anthropogenic processes to measurable indicators of ecosystem functioning. Within this framework, employees' ecological behavior is conceptualized not as an external social factor but as a sustained anthropogenic process embedded within post-mining ecosystem dynamics, operating alongside biophysical state variables and environmental constraints.

The results demonstrate that institutional pathways, including corporate environmental responsibility, ecological awareness, and employees’ well-being, do not directly alter ecosystem functioning. Instead, their ecological influence is mediated through employees’ ecological behavior, which functions as a dynamic anthropogenic driver shaping recovery trajectories. As illustrated in **Figure 2,** the proposed pathway model suggests how employee behaviors may contribute to employee-mediated actions such as participation in revegetation, adherence to waste management protocols, and moderation of energy use, which represent repeated micro-scale interventions that cumulatively influence vegetation recovery, carbon cycling, and soil stabilization.

From an applied ecology perspective, these behaviors are functionally analogous to biotic processes in natural systems. Just as organismal activity regulates material flows and energy transfer, sustained human-mediated interventions regulate disturbance regimes and recovery pathways in anthropogenically transformed landscapes. The empirical findings support the proposition that under conditions of intensive disturbance, human behavior can operate as a restorative ecological force rather than solely as a source of degradation.

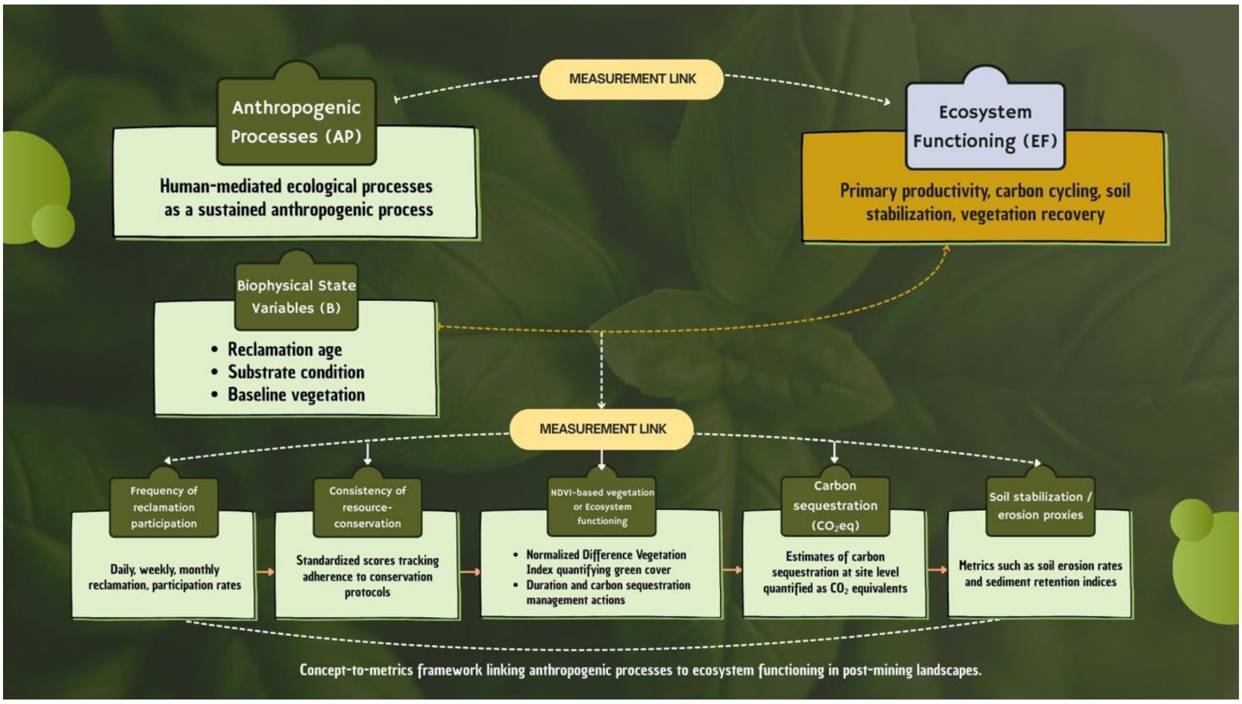

Figure 2. Proposed pathway model to metrics framework linking anthropogenic processes to ecosystem function in post mining landscape.

The transformation of post-mining landscapes through reclamation and revegetation suggests that ecosystem recovery is an emergent property of coordinated anthropogenic inputs rather than a solely biophysical process. This finding is consistent with restoration ecology literature emphasizing the role of sustained human intervention in accelerating ecosystem recovery [8,19].

Biophysical state variables, including reclamation age, substrate condition, and baseline vegetation, modulate the strength of ecosystem functioning and anthropogenic processes. Environmental constraints such as climate and geomorphology further influence recovery trajectories by shaping the responsiveness of ecosystems to human intervention. This interaction between anthropogenic processes and site-specific conditions is consistent with restoration ecology theory, which emphasizes that recovery outcomes emerge from the alignment of sustained intervention with ecological context.

Furthermore, the results highlight that the mining company's ecological outcomes such as a carbon reduction of 289,772 t CO_2eq and 48% vegetation recovery cannot be attributed solely to management decisions. They are emergent properties of employees' ecological behavior as anthropogenic drivers, where corporate policy provides the structural framework and employees' behavior supplies the ecological agency. This interactive dynamic aligns with the adaptive cycle model of resilience, where system renewal depends on the capacity of agents to reorganize ecological and social resources after disturbance [2].

The feedback pathways depicted in **Figure 2** further highlight the adaptive nature of human ecosystem interactions in post-mining landscapes. Improvements in visible ecosystem conditions, such as increased vegetation cover or stabilized reclaimed areas, reinforce the persistence of employees' ecological behavior by stabilizing anthropogenic input over time. Rather than a linear cause-and-effect relationship, the framework illustrates reciprocal feedback through which ecosystem recovery and human-mediated processes co-evolve, a defining feature of social ecological systems.

The observed ecological outcomes, including substantial carbon emission reductions and measurable vegetation recovery, cannot be attributed solely to managerial decisions or site rehabilitation plans [32–34]. Instead, they emerge from the interaction between institutional governance and sustained employees' ecological behavior, where organizational structures provide continuity and human actions supply the operational ecological process [35–37]. This dynamic aligns with adaptive cycle models of resilience, in which system renewal depends on the capacity of agents to reorganize ecological and social resources following disturbance [38].

Within restoration ecology, ecosystem recovery in post-disturbance landscapes is increasingly understood as a process that is socially mediated yet ecologically constrained [39–41]. Restoration outcomes depend not only on species selection or site preparation but also on the consistency, intensity, and temporal persistence of human intervention [42,43]. In this context, employees' ecological behavior represents a form of organized anthropogenic input that accelerates and stabilizes ecosystem recovery trajectories in post-mining systems.

Ecological theory further supports this interpretation through scale-dependent processes [44,45]. Repeated small-scale interventions, when sustained over time, generate emergent landscape-level patterns of ecosystem functioning. In post-mining landscapes, cumulative employees mediated actions, therefore operate as scaling pathways linking individual behavior to measurable ecological outcomes [46,47]. This process was based on interpretation, which reinforces the central claim of this study: ecosystem functioning in human-dominated systems emerges from the interaction between sustained anthropogenic processes and biophysical recovery dynamics.

4.5. Ecological Implications

The findings of this study carry several implications for applied ecology and restoration ecology in anthropogenically transformed landscapes [48,49]. First, the results reinforce the view that ecosystem functioning in post-mining systems cannot be fully explained by biophysical variables alone. Instead, sustained anthropogenic processes mediated through consistent human ecological behavior constitute an integral component of ecosystem dynamics [50]. This supports emerging ecological perspectives that position human activity as a functional driver within human-dominated ecosystems rather than solely as an external disturbance.

Second, the study highlights the importance of process stability in ecosystem recovery. Critical ecological functions, including carbon sequestration, soil stabilization, and vegetation recovery, are shown to depend on the continuity and persistence of anthropogenic interventions over time. From an ecological standpoint, this suggests that recovery trajectories are sensitive not only to the type of restoration actions implemented but also to their temporal consistency. Restoration strategies that fail to maintain stable employees may therefore produce slower or less resilient ecosystem recovery, even under favorable biophysical conditions [51].

Third, the results underscore the relevance of scale-dependent ecological processes in post-disturbance recovery. Repeated micro-scale human interventions, when sustained over time, can generate emergent landscape-level patterns of ecosystem functioning. This finding aligns with ecological theory emphasizing that cumulative small-scale processes drive large-scale ecological outcomes. In post-mining landscapes, employees' ecological behavior thus operates as a scaling pathway linking localized actions to broader ecosystem recovery trajectories.

Finally, the study contributes to restoration ecology by providing empirical support for the concept that ecosystem recovery is a socially mediated yet ecologically constrained process. While biophysical site conditions set the boundaries of recovery potential, the realization of ecosystem functioning depends on the alignment between ecological context and sustained anthropogenic inputs. This perspective advances applied ecology by offering a framework for understanding how employees interact with biophysical dynamics to shape ecosystem functioning in intensively disturbed systems.

4.6. Methodological Limitations and Implications for Future Research

This study has several limitations that should be considered when interpreting the results, despite its contributions. To begin with, the dependence on self-reported indicators of ecological behavior may give rise to bias associated with social desirability and individual subjectivity. While these measures capture the stability of anthropogenic processes, they do not directly quantify the intensity of biophysical change at the site level.

Second, the analysis is based on a single post-mining corporate system, which may constrain the applicability of the proposed framework across different industrial sectors or ecological settings. Recovery trajectories and the strength of anthropogenic pathways are likely to vary across ecosystems with different disturbance histories, climatic conditions, and restoration regimes.

Future research should adopt multi-level ecological designs that integrate behavioral indicators with direct biophysical measurements. The incorporation of remote sensing data (e.g., NDVI-based vegetation dynamics), soil carbon assessments, biodiversity indices, or erosion metrics would allow more robust testing of the causal pathways linking anthropogenic processes to ecosystem functioning. Longitudinal and cross-site comparative studies would further enable evaluation of how the stability and persistence of employees influence recovery trajectories across different industrial and ecological settings.

5. Conclusions

This study suggests that ecosystem functioning in post-mining landscapes emerges from sustained interactions between anthropogenic processes and biophysical recovery dynamics. Employees' ecological behavior operates as a functional anthropogenic driver that mediates the effects of institutional and individual-level conditions on vegetation recovery, carbon sequestration, and soil stabilization. Rather than acting as an external social factor, human behavior is embedded within ecosystem processes, shaping recovery trajectories through repeated, small-scale interventions sustained over time.

By integrating empirical evidence with a process-based conceptual framework, this research advances applied ecology by illustrating how human-mediated actions can function analogously to biotic processes in regulating ecosystem functioning under intensive disturbance. The findings emphasize that recovery outcomes depend not only on-site conditions and restoration techniques but also on the temporal continuity and stability of anthropogenic ecological inputs.

Overall, the study contributes to ecological theory by framing post-mining ecosystems as dynamic human–ecological systems in which ecosystem functioning is co-produced through feedback between sustained anthropogenic processes and biophysical constraints. This perspective extends restoration ecology by providing a transferable framework for analyzing human-mediated ecosystem recovery in other highly disturbed landscapes.

Author Contributions

Conceptualization, S.A., M.I.A., N.I., J.P. and R.K.; methodology, S.A., M.I.A., N.I., J.P. and W.I.R.S.; software, W.I.R.S.; investigation, S.A.; resources, M.E.S.; writing—original draft preparation, S.A., M.I.A., R.K. and W.I.R.S.; writing—review and editing, S.A., M.I.A., N.I., J.P., R.K., W.I.R.S., M.E.S., Y.R. and F.; supervision, M.I.A., N.I., J.P., R.K., W.I.R.S. and F. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Ethical review and approval were waived for this study as it involved non-invasive survey and interview data collected from employees, without the collection of sensitive personal information and posing no risk to participants.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. Participation was voluntary, and all participants were informed about the purpose of the research, with assurances of confidentiality and anonymity of their responses.

Data Availability Statement

The data supporting the findings of this study are not publicly available due to confidentiality and privacy considerations, but are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors acknowledge the use of AI language tools (Claude by Anthropic) for language polishing, grammar correction, and writing assistance during manuscript preparation. All scientific concepts, research design, data collection, statistical analyses, and interpretations are entirely original work by the authors. AI tools were used solely as writing assistants to improve clarity and readability, not for generating scientific content, ideas, methodologies, or conclusions. The authors subsequently reviewed and edited the content as necessary and take full responsibility for the final content of the published article.

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