



Development of a Center of Excellence Model for Post-Mining Reclamation Based on Circular Economy and Biodiversity Conservation

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Article History:

Received: 03-09-2026

Revised: 14-09-2026

Accepted: 26-09-2026

Keywords: Biodiversity Conservation, Circular Economy, Living Laboratory, Post-Mining Reclamation

Abstract: Post-mining land reclamation needs to extend beyond restoring vegetation cover to rebuilding ecological functions, improving resource efficiency, and supporting continuous learning. This program aimed to develop a Center of Excellence (CoE) model for post-mining land reclamation based on circular economy principles and biodiversity conservation at the Temandang Limestone Quarry. The program was implemented through site asset and potential identification, resource and stakeholder mapping, integration of reclamation and conservation practices, implementation of circular economy innovations, and model evaluation and documentation. The results showed that the site comprised 126.26 ha of revegetated land, with 332,151 plants representing 21 species. Circular economy principles were implemented by converting vegetation litter, livestock manure, and sawdust into compost blocks, which were characterized and applied to 27 teak plants. This implementation established a biological cycle of vegetation–litter–biomass processing–compost blocks–planting–vegetation. The program resulted in a living-laboratory-based CoE model integrating four pillars—ecological restoration, circular economy, biodiversity conservation, and learning and replication—through interconnected resource, ecological, and knowledge circularity mechanisms. The model expands the role of reclaimed post-mining areas into spaces for demonstration, innovation, learning, and the development of sustainable post-mining management practices.

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INTRODUCTION

Mining operations have a finite lifespan determined by the availability of economically recoverable mineral reserves. However, the ecological and social impacts associated with landscape alteration may persist long after extraction activities have ceased. Mine closure should therefore not be regarded merely as the end of mining operations, but as part of a transition toward safe, stable, productive, and sustainable post-mining land use. Measham et al. (2024) emphasized that the conventional *mine closure* paradigm needs to be broadened toward a *post-mining transition* perspective. The success of post-mining management is determined not only by compliance with technical closure requirements but also by the capacity of the area to generate ecological, social, and

economic value after mining operations have ended. This perspective is consistent with Tibbett (2024), who argued that mining-induced landscape transformation requires an approach that goes beyond rehabilitation or revegetation toward post-mining ecosystem reconstruction.

This paradigm shift has implications for how reclamation success is assessed. Successful reclamation cannot be demonstrated solely by land stabilization and vegetation establishment; it should also reflect the recovery of ecological functions. Post-mining ecosystems should be managed to sustain soil functions, nutrient cycling, vegetation structure, habitat provision, and ecological processes over the long term. International principles and standards for the ecological restoration of mine sites emphasize ecosystem integrity, resilience, self-sustainability, benefits to both people and nature, and the application of scientific knowledge and long-term adaptive management (Young et al., 2022). Harries et al. (2024) further demonstrated that mine restoration assessments often rely on a limited set of indicators and therefore may not fully represent ecosystem development toward a self-sustaining and ecologically functional state.

In Indonesia, these challenges are particularly relevant because many mining areas are located within tropical landscapes characterized by high ecological complexity and biodiversity. Pratiwi et al. (2021) highlighted that post-mining land management in Indonesia requires a science-based approach that considers soil characteristics, plant species selection, post-mining material management, and long-term landscape functionality. Iskandar et al. (2022) demonstrated that soil chemical properties, including pH, organic carbon, nitrogen, and available phosphorus, play an important role in determining the growth of revegetation plants in post-mining landscapes in East Kalimantan. These findings indicate that revegetation should be positioned as part of ecosystem reconstruction that links improvements in the growing medium with vegetation development and the recovery of ecological processes.

Vegetation plays a strategic role in this recovery process. A meta-analysis by Yuan et al. (2023), based on 4,838 observations from 175 publications, showed that vegetation restoration in post-mining lands increased soil organic carbon, nitrogen, phosphorus, and the activity of several soil enzymes. The magnitude of these responses was influenced by mine type, climate, restoration duration, moisture conditions, and initial soil characteristics. A systematic review by Navarro-Ramos et al. (2022) covering 203 studies also showed that the success of active revegetation is influenced by local conditions, plant species, and applied treatments. The use of organic amendments was among the interventions that showed the most consistent positive responses in plant growth. Vegetation therefore serves not only as land cover but also contributes to the restoration of carbon cycling, nutrient dynamics, and the ecological structure of post-mining areas.

Vegetation recovery also provides a foundation for biodiversity conservation. Large-scale forest restoration at an Amazonian mining site demonstrated that developing vegetation toward a more complex ecosystem structure can generate biodiversity gains across multiple biotic groups (Gastauer et al., 2024). At the landscape scale, successful reclamation should also consider ecological connectivity. Hernández-Santín et al. (2024) showed that restoring mined areas toward natural ecosystems resulted in greater landscape connectivity than rehabilitation for agricultural land use in most of the scenarios analyzed. Nevertheless, the presence of vegetation alone does not necessarily indicate comprehensive biodiversity recovery. Species composition, community structure, habitat functions, and ecosystem development require long-term evaluation to determine restoration success (Campbell et al., 2024).

In addition to supporting biodiversity, vegetation development on post-mining land has the potential to enhance ecosystem services, including carbon storage. Vegetation restoration enables atmospheric carbon to be captured through photosynthesis and stored in plant biomass and soil organic carbon. Zhu et al. (2024) showed that ecological restoration in mining areas has carbon sequestration potential that varies according to vegetation type, restoration duration, and environmental conditions. Yuan et al. (2023) similarly reported increases in soil organic carbon following vegetation restoration across different post-mining lands. Carbon-related functions should therefore not be considered separately from other ecological functions. Reclamation should instead be directed toward the development of multifunctional ecosystems capable of supporting soil recovery, biodiversity, nutrient cycling, habitat connectivity, biomass production, and carbon storage.

Alongside ecological recovery, the circular economy paradigm offers a new perspective for post-mining land management. A circular economy treats residual materials not merely as waste but as resources whose value can be recovered through reuse, processing, and recirculation. Pavloudakis et al. (2024) demonstrated that the principles of reduce, reuse, recycle, and recover can be integrated into mine closure planning to reduce resource losses and generate new value from available materials. A systematic review by Cotrina-Teatino and Marquina-Araujo (2025), covering 136 publications, showed that circular economy applications in the mining industry remain predominantly focused on waste management, tailings, regulation, and value chains. The integration of circular economy principles with sustainable mine closure and land rehabilitation therefore remains an area requiring further development.

Within the context of reclamation, the circular economy can be extended from mineral material circulation to the circulation of biological resources. Vegetation established in reclaimed areas produces biomass in the form of leaves, branches, and litter containing carbon and nutrients. This biomass can be processed and returned to the system to support subsequent vegetation growth. Soria et al. (2021) demonstrated that organic amendments derived from residual materials applied to limestone quarry soils improved organic carbon, nitrogen, available phosphorus, water retention, microbial activity, and vegetation growth. A subsequent study showed that organic amendments derived from recycled wastes also supported fungal community development and the recovery of soil biological functions in a restored limestone quarry (Rodríguez-Berbel et al., 2022). These findings provide opportunities to integrate ecosystem recovery with the recovery and recirculation of biological resources (biological resource recovery).

This opportunity is particularly relevant to the conditions at the Temandang Limestone Quarry of PT Semen Indonesia (Persero) Tbk, Tuban Plant. Reclaimed and revegetated areas generate biomass, particularly teak (*Tectona grandis*) leaf litter, while the surrounding area provides other sources of organic material, including livestock manure and sawdust. The program utilizes these resources as raw materials for compost blocks, which are subsequently reused to support planting activities. This mechanism establishes a resource flow of vegetation → litter → biomass processing → compost blocks → planting → vegetation. The cycle represents the application of circular economy principles to biological resources within a reclaimed landscape. The block form also enables organic material to be applied directly to planting points and root zones. Consequently, the innovation not only reduces organic residues but also returns locally available resources to the vegetation recovery process. This biomass circulation framework constitutes one of the principal components developed within the program.

The development of sustainable reclamation practices, however, requires more than technical innovation. The knowledge and experience generated must be documented, evaluated, exchanged, and disseminated to enable replication by other stakeholders. Favretto et al. (2022) demonstrated that knowledge exchange in restoration initiatives can enhance stakeholder engagement, mutual learning, and understanding of restoration techniques. In this context, the living laboratory concept is particularly relevant because it positions real-world environmental challenges as spaces for collaboration, experimentation, learning, and the co-creation of solutions. Through the Citarum Living Lab, Hadfield et al. (2024) demonstrated how a transdisciplinary approach can bring together multiple actors to develop shared visions and solutions to environmental challenges. This approach provides a conceptual foundation for developing reclaimed mining areas as learning environments that connect field practices, innovation, and knowledge exchange.

Although previous studies have addressed post-mining ecosystem restoration, circular economy, biodiversity, ecosystem services, and stakeholder participation, these dimensions are still frequently examined separately. Worden et al. (2024) emphasized the importance of interdisciplinary and multi-stakeholder approaches to post-mining land-use planning. Measham et al. (2024) further noted that successful post-mining transition models that can be transferred across different contexts remain relatively limited. These conditions indicate the need for an implementable model that integrates ecosystem recovery, circular economy, biodiversity conservation, learning, and the replication of reclamation practices within a single landscape. Such a model is necessary to ensure that reclamation does not develop merely as a collection of isolated technical interventions, but rather as an integrated management system capable of generating knowledge, innovation, and practices that can be continuously improved.

In response to this need, a Center of Excellence for Post-Mining Reclamation Based on Circular Economy and Biodiversity Conservation was developed. The post-mining area is positioned as a living laboratory for developing, implementing, evaluating, documenting, and disseminating environmental management practices. The novelty of the program lies not in a single technology but in the integration of ecological recovery, organic resource recirculation, biodiversity conservation, and the learning and replication of reclamation practices within a unified site management model. The concept also creates opportunities for community and local stakeholder participation through the provision and utilization of organic resources, application of innovations, knowledge exchange, and program network development.

Accordingly, this community engagement program aimed to develop a Center of Excellence model for post-mining land reclamation based on circular economy principles and biodiversity conservation as a platform for demonstrating, innovating, learning, and replicating sustainable environmental management practices. Specifically, the program sought to integrate established reclamation practices, optimize the utilization of local resources through circular innovations, strengthen the ecological functions and biodiversity potential of the area, and establish a knowledge base that can be utilized by companies, communities, academics, government institutions, and other stakeholders. Through this approach, post-mining areas are expected not only to fulfill reclamation functions but also to evolve into learning and innovation environments that support adaptive and sustainable environmental management.

IMPLEMENTATION METHODS

Program Approach and Design

The community engagement program employed a practice-based model development approach. This approach was selected because the program was not intended to examine causal relationships through controlled experiments, but rather to integrate reclamation practices, local resource utilization, biodiversity conservation, environmental innovation, and learning into a Center of Excellence (CoE) model for post-mining land reclamation. Within this framework, the reclaimed area was positioned as a *living laboratory* in which environmental management practices could be implemented, observed, documented, and further developed as learning resources.

The model was developed progressively through site potential identification, stakeholder and resource mapping, integration of reclamation and conservation practices, implementation of circular economy innovations, initial evaluation, and formulation of future directions for CoE development. This approach is consistent with the *living laboratory* concept, which positions real-world environments as spaces for learning and solution development through the involvement of multiple actors (Hadfield et al., 2024). A multi-stakeholder approach is also relevant to post-mining management because post-mining land use requires the integration of ecological, social, technical, and institutional dimensions (Worden et al., 2024).

This design enabled the program to be evaluated based on the integration process and implementation outputs, rather than through comparisons between treatment and control groups. Accordingly, the analysis focused on explaining how existing site components could be integrated into a CoE model and identifying practices with the potential for further development, documentation, and replication.

Location, Target Groups, and Stakeholders

The program was implemented in the reclamation and revegetation area of the Temandang Limestone Quarry, Tuban Plant of PT Semen Indonesia (Persero) Tbk. The site is part of a 752.8-ha Production Operation Mining Permit (*Izin Usaha Pertambangan Operasi Produksi*, IUP OP) area. Geographically, the area is located between 6°52'04"–6°54'00" S and 111°54'20"–111°57'10" E, covering Temandang, Pongpongan, and Senori Villages in Merakurak District and Sumberarum Village in Kerek District.



Figure 1. Satellite image of the Temandang Limestone IUP OP area

The site was selected because it already supported reclamation and revegetation activities, vegetation biomass resources, biodiversity conservation practices, and opportunities for developing innovations based on locally available resources. The program targeted reclamation and revegetation managers as well as communities

surrounding the operational area. Program documentation recorded 16 beneficiaries from several hamlets and villages surrounding the site. Within the CoE development framework, beneficiaries were positioned not only as potential users of the innovations but also as part of the stakeholder ecosystem that could support local resource utilization and subsequent program development.

Program implementation involved several stakeholders with distinct roles. PT Semen Indonesia (Persero) Tbk Tuban Plant was responsible for program development, management, and implementation; the Mining and Raw Materials Department was responsible for reclamation, revegetation, and biodiversity conservation management; Griya Winih supported seedling provision; and reclamation and revegetation managers were involved in applying compost blocks during planting activities. Surrounding communities were positioned as beneficiaries and prospective users, while local farmers and livestock farmers contributed organic materials in the form of livestock manure. Farmer groups and company-assisted community groups were mapped as prospective managers and users of the innovation in subsequent stages of development.

Stages of Center of Excellence Development

The CoE was developed through a series of stages connecting the site's ecological potential, local resources, circular innovations, and learning functions. Conceptually, the implementation process consisted of site asset identification, resource and stakeholder mapping, integration of environmental practices, demonstration of circular economy innovations, and model evaluation and documentation.

The first stage involved the identification of site assets and potential. The identification process covered existing reclamation and revegetation conditions, established vegetation, generated biomass, conservation practices, and organic resources available around the site. This stage was necessary to ensure that the CoE was developed based on actual practices and resources rather than as a facility detached from the existing reclamation system. The available technical inventory recorded 332,151 individual plants representing 21 vegetation species, with teak (*Tectona grandis*) as one of the dominant species. This vegetation also generates litter biomass that can be reutilized within the reclamation system.



Figure 2. Compost Block Production Process from Locally Available Biomass and Organic Materials

The second stage involved resource-flow and stakeholder mapping. The mapping process was conducted to identify relationships among biomass sources, organic material providers, site managers, beneficiaries, and potential users of the innovation. This stage

was used to establish a circular economy framework at the site level. Biomass generated by reclamation vegetation was positioned as a resource that could be returned to the system, while livestock manure supplied by local farmers and livestock farmers served as an additional source of organic material. This approach enabled reclamation, biomass management, livestock farming, and organic product utilization to be mapped as an interconnected resource chain.

The third stage involved the integration of reclamation practices and biodiversity conservation. At this stage, established vegetation was regarded not merely as an indicator of revegetation success but as part of the ecological assets of the CoE. Vegetation diversity, biomass production, habitat functions, and site management practices were positioned as the basis for developing conservation and learning functions. Because the available data did not provide comprehensive biodiversity monitoring across all biotic groups, the biodiversity component was treated as the integration of conservation practices and conservation potential within the site, rather than as a quantitative assessment of changes in biodiversity indices.

The fourth stage consisted of the demonstration of circular economy innovation through compost block development. This innovation was selected as an implementation example because it connects biomass generated from reclamation activities with subsequent planting requirements. The litter used primarily originated from teak vegetation and was combined with cattle manure and sawdust. The solid-material formulation consisted of 30% leaf litter, 40% cattle manure, and 30% sawdust. The mixture was moistened with water containing EM4 bioactivator, followed by the addition of tapioca starch solution as a binding agent. The materials were homogenized and molded into blocks measuring $20 \times 20 \times 15$ cm, with an 8-cm-diameter planting hole, and then sun-dried for 10–15 days until the block structure became stable.

The resulting product was subsequently characterized through laboratory analyses of organic carbon (C-organic), nitrogen (N), P_2O_5 , K_2O , C/N ratio, pH, and moisture content. Characterization was conducted to provide a technical basis for the product used as a demonstration of circular innovation. The compost blocks were then applied to reclamation plants by placing seedlings in the central planting holes, positioning the blocks at the planting sites, covering them with topsoil, and watering the plants. Field implementation was documented for 27 teak plants, with plant height, stem diameter, and number of leaves observed as indicators of initial application performance.



Figure 3. implementation of compost blocks at planting points within the reclaimed limestone quarry

Through these stages, the compost block innovation was not treated as a stand-alone activity but as a demonstration of a circular resource flow: vegetation → litter → biomass processing → compost blocks → planting → vegetation. This mechanism provides implementation-based evidence that reclaimed areas can generate resources that are subsequently reused to support continued site management.

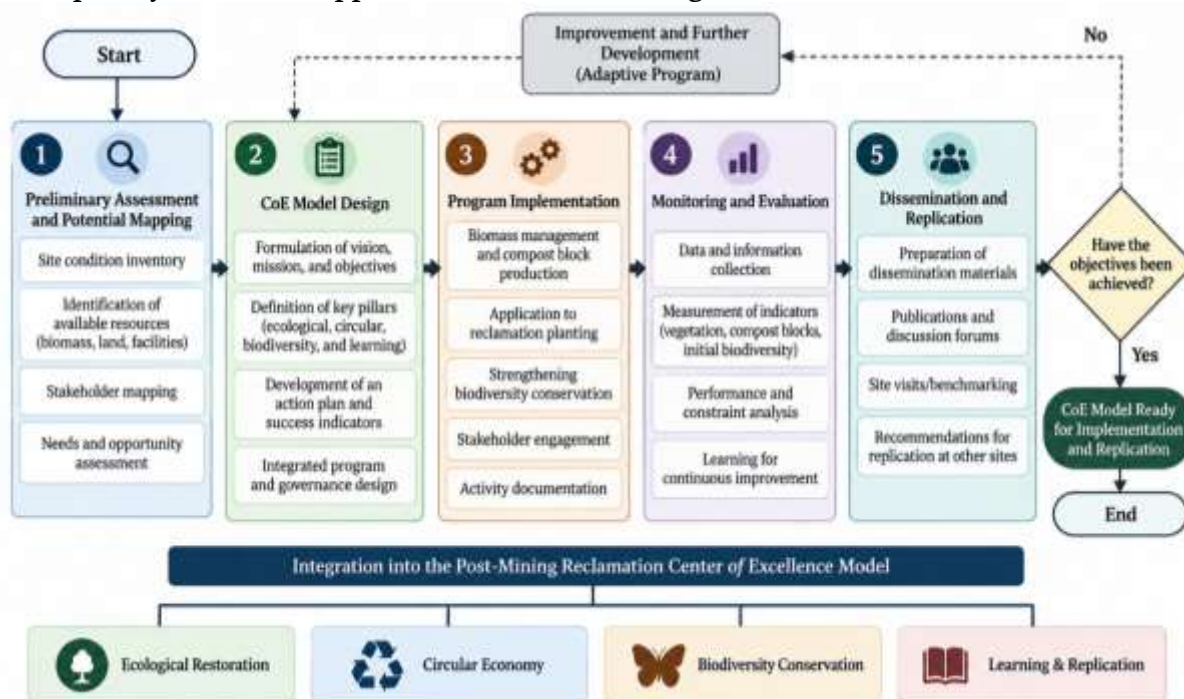


Figure 4. Flowchart of the Development Process for the Post-Mining Reclamation Center of Excellence Model

Data Collection and Analysis

Program data were obtained through activity documentation, inventories of resources and stakeholders, technical site-management data, laboratory analyses of compost blocks, and field implementation observations. Multiple data sources were used because the CoE was developed as a site-based model encompassing ecological, technical, circular, and social dimensions and therefore could not be adequately represented by a single indicator.

The data were analyzed using a descriptive-integrative approach. Site and vegetation data were used to characterize the ecological assets supporting CoE development. Stakeholder data were analyzed according to their roles and interrelationships within program implementation. Compost block characteristics were evaluated based on the chemical parameters of the product, whereas field application data were used to describe the initial performance of the implemented innovation. Because the available documentation did not indicate the use of a control group, randomization, or comparative treatments, the compost block application data were not used to statistically infer causal relationships.

The circular economy component was analyzed through material flow mapping by tracing biomass sources, transformation processes, product forms, and the reuse of products within the site. This approach is relevant to circular economy principles in the Fomining sector, which emphasize the recovery of material value and resource reuse in post-mining management (Pavloudakis et al., 2024; Cotrina-Teatino & Marquina-Araujo,

2025). The vegetation–litter–compost blocks–planting–vegetation flow was used as an indicator of biological resource circulation at the implementation level.

Finally, the results were mapped into four dimensions of CoE development: (1) ecological restoration and management, (2) circular economy and resource innovation, (3) biodiversity conservation, and (4) learning, documentation, and replication potential. This mapping was used to assess the extent to which existing practices could contribute to the establishment of the CoE model as a *living laboratory*. Learning and replication were considered important dimensions because knowledge exchange can enhance engagement and learning in restoration programs (Favretto et al., 2022), while the *living laboratory* approach enables field practices to be developed as spaces for collaboration and knowledge creation (Hadfield et al., 2024).

RESULT AND DISCUSSION

Ecological Potential and Biodiversity as the Foundation for Center of Excellence Development

The assessment demonstrated that the Temandang Limestone Quarry possesses substantial ecological, technical, and resource assets that provide a foundation for developing a post-mining reclamation *Center of Excellence* (CoE). The Production Operation Mining Permit area covers 752.80 ha, of which 126.26 ha had been revegetated by 2026. A total of 332,151 plants representing 21 species had been established across the reclaimed landscape. Several planting configurations, including 2×3 m, 1×2 m, 3×4 m, and 3×5 m, were applied according to plant species and site conditions.

Table 1. Site potential as a foundation for Center of Excellence development

Parameter	Result	Relevance to the CoE
Production Operation Mining Permit area	752.80 ha	Spatial basis for post-mining management development
Revegetated area by 2026	126.26 ha	Demonstration platform for reclamation practices
Number of plants	332,151 unit	Ecological asset and biomass source
Recorded vegetation richness	21 species	Initial biodiversity baseline
Dominant vegetation	Teak (<i>Tectona grandis</i>)	Source of litter biomass
Planting methods	Topsoil spreading and row planting	Technical practices for documentation and learning
Organic resource sources	Litter, livestock manure, sawdust	Basis for circular economy innovation

These conditions indicate that the CoE is being developed not on a newly reclaimed site, but within a reclaimed landscape where ecological assets and established management practices are already present. This distinction is important because a CoE functioning as a *living laboratory* requires tangible objects and processes through which demonstration, observation, innovation testing, learning, and evaluation can take place. Tibbett (2024) emphasized that post-mining management should extend beyond the establishment of vegetation cover toward ecosystem reconstruction capable of restoring ecological processes and functions. Similarly, Young et al. (2022) identified ecosystem integrity, resilience,

ecological functionality, and the capacity for self-sustaining development as fundamental principles of mine-site restoration.

The presence of 21 vegetation species adds an important ecological dimension to CoE development, as reclamation may progressively evolve from land-cover establishment toward habitat recovery and broader ecosystem functioning. Vegetation provides structural habitat, biomass, litter, food resources, and microhabitats that may support other organisms. Yuan et al. (2023) demonstrated that vegetation restoration in post-mining landscapes can enhance soil organic carbon, nitrogen, phosphorus, and soil enzyme activity. At the ecosystem scale, Gastauer et al. (2024) reported positive biodiversity responses across multiple biotic groups following forest restoration in mined landscapes, while Hernández-Santín et al. (2024) showed that post-mining land-use trajectories can substantially influence habitat connectivity at the landscape scale.

Nevertheless, the presence of 21 vegetation species should not be interpreted as evidence that biodiversity has fully recovered or increased. The available dataset does not include relative abundance, diversity and evenness indices, natural regeneration, community structure, or faunal assemblages. Accordingly, the vegetation inventory is more appropriately regarded as an ecological baseline for establishing a systematic biodiversity-monitoring framework within the CoE. This cautious interpretation is consistent with Harries et al. (2024) and Campbell et al. (2024), who emphasized the need for comprehensive ecological indicators to assess restoration trajectories and ecosystem development in post-mining environments.

The ecological assets of the site therefore perform a dual function within the proposed CoE model. First, established vegetation represents an outcome of reclamation that can be monitored to understand the development of ecological functions. Second, the vegetation generates biomass that can be recovered and transformed into inputs for subsequent management interventions. This dual role provides a critical transition from ecological restoration toward biological resource circularity.

Biomass Circularity and Compost Block Innovation

Resource mapping revealed that established vegetation within the reclaimed landscape generates biomass in the form of fallen leaves, branches, and other plant residues. The litter utilized in the program was derived primarily from teak (*Tectona grandis*), supplemented by biomass from *Senna siamea*, *Samanea saman*, *Azadirachta indica*, and *Swietenia macrophylla*. Within the proposed model, these materials were not treated merely as residual biomass but as biological resources whose value could be recovered and reintegrated into the reclamation system. Vegetation-derived biomass was subsequently combined with locally available organic materials, including livestock manure and sawdust, to produce compost blocks.

This pathway illustrates that circular economy applications in mine reclamation need not be confined to the reuse of mineral residues or mine waste. Pavloudakis et al. (2024) demonstrated that circular economy principles in mine closure can promote resource-loss reduction, material reuse, and value recovery from locally available resources. Meanwhile, Cotrina-Teatino and Marquina-Araujo (2025) showed that circular economy discourse within the mining sector remains largely concentrated on mining waste, tailings, regulatory frameworks, and value chains. The present program extends this perspective toward biological circularity, whereby biological materials generated following ecological restoration are recovered and recirculated within the reclaimed landscape.



Figure 5. Biological circular economy pathway within the reclaimed landscape

Compost blocks represent the operational manifestation of this circular pathway. The product was formulated using 30% leaf litter, 40% cattle manure, and 30% sawdust and molded into blocks measuring 20 × 20 × 15 cm, with an 8-cm-diameter central planting hole. The block configuration enables organic material to be placed locally at individual planting points and in close proximity to the developing root zone.

Laboratory characterization showed that the compost blocks contained 34.89% organic carbon, 1.80% nitrogen, 0.42% P_2O_5 , and 0.48% K_2O , with a C/N ratio of 19.33, a pH of 5.50, and a moisture content of 20.00%.

Table 2. Chemical characteristics of the compost blocks

Parameter	Result
Organic carbon	34.89%
Nitrogen (N)	1.80%
P_2O_5	0.42%
K_2O	0.48%
C/N ratio	19.33
pH	5.0
Moisture content	20.00%

The organic carbon content indicates a substantial organic fraction within the product, while the presence of N, P, and K confirms the availability of macronutrients relevant to the growing medium. Organic matter is particularly important in limestone quarry reclamation because organic amendments can contribute to improvements in soil properties and biological processes. Soria et al. (2021) demonstrated that organic amendments applied to limestone quarry soils improved organic carbon, nitrogen, available phosphorus, water retention, and soil biological functioning. Rodríguez-Berbel et al. (2022) further reported that recycled organic residues used as soil amendments supported the development of fungal communities in restored quarry soils.

The compost blocks were subsequently applied to 27 teak plants. Plant height, stem diameter, and number of leaves were recorded as indicators of initial vegetative performance. Plant height ranged from 31 to 130 cm, stem diameter from 1.11 to 3.20 cm, and leaf number from 8 to 22 leaves per plant.

Table 3. Initial plant performance following field implementation of compost blocks

Parameter	n	Minimum	Maximum	Range
Plant height (cm)	27	31	130	99
Stem diameter (cm)	27	1.11	3.20	2.09
Number of leaves	27	8	22	14

These observations demonstrate that the innovation progressed beyond formulation and laboratory characterization to field-scale implementation under actual reclamation conditions. However, the results cannot be used to infer that compost blocks caused improvements in plant growth because the implementation did not include a control group, randomization, or pre- and post-treatment measurements. The observations should therefore be interpreted as evidence of implementation feasibility and preliminary field performance, rather than definitive evidence of agronomic effectiveness. This interpretation is also consistent with Navarro-Ramos et al. (2022), who demonstrated that post-mining revegetation performance is influenced by interactions among site conditions, plant species, and restoration treatments.

Within the CoE framework, the significance of compost blocks therefore extends beyond their physicochemical characteristics. The product functions as a technological artifact through which biological resource recirculation can be demonstrated in practice. It connects the outputs of previous reclamation activities, in the form of vegetation-derived biomass, with inputs required for subsequent planting activities. The innovation consequently performs three interrelated functions: resource-value recovery, localized technical application, and demonstration of circular economy principles.

This finding reveals an important transformation in the relationship between reclamation and resource use. Under a linear model, vegetation constitutes the end product of reclamation, while fallen biomass may eventually be regarded as residual material. Under a circular model, vegetation simultaneously becomes an ecological output and a source of new material inputs. The reclaimed landscape thus begins to exhibit a *closed-loop biological resource pathway*, although the degree of material circularity remains to be quantitatively assessed in subsequent stages of CoE development.

Stakeholder Integration and Learning within a Living Laboratory

The development of the CoE integrates not only ecological and technological components but also relationships between site resources and surrounding stakeholders. Farmers and livestock farmers were mapped as potential suppliers of organic materials, particularly livestock manure; local communities were positioned as beneficiaries and prospective users of the innovations; and farmer groups and company-assisted community groups were identified as potential users and managers during subsequent development stages. Program records identified 16 individuals as beneficiaries. However, the available data do not include quantitative measurements of changes in knowledge, skills, income, adoption rates, or production autonomy. Social outcomes at this stage should therefore be interpreted as evidence of an emerging stakeholder-engagement platform and opportunities for knowledge transfer, rather than as demonstrated community empowerment outcomes.

Such stakeholder engagement becomes particularly important when the reclaimed landscape is conceptualized as a *living laboratory*. Within this framework, reclamation generates field experience and empirical data; established vegetation generates biomass; biomass becomes a resource for innovation; innovations are implemented and observed; and implementation outcomes are documented to inform subsequent management practices. The reclaimed landscape therefore begins to function not merely as an implementation site, but as a practice-based learning infrastructure.

This process establishes a knowledge pathway: field practice → observation → documentation → evaluation → learning → improvement → subsequent implementation. Favretto et al. (2022) demonstrated that knowledge exchange can strengthen stakeholder engagement and learning within restoration and rehabilitation initiatives. Hadfield et al. (2024) similarly showed that living laboratories can provide real-world settings in which knowledge, stakeholders, and environmental challenges are brought together through collaborative solution development. In post-mining contexts, Worden et al. (2024) emphasized the importance of multidisciplinary and multi-stakeholder approaches to post-mining land-use planning. Collectively, these perspectives support the positioning of the CoE as a platform connecting practice, actors, empirical evidence, innovation, and learning.

From this perspective, the CoE should not be understood solely as a physical site, but rather as an emerging knowledge infrastructure. The value of the site is therefore not determined merely by the number of activities undertaken, but by its capacity to transform field experience into data, data into actionable knowledge, and knowledge into improved practices that can subsequently be transferred or adapted elsewhere.

Nevertheless, the *living laboratory* function remains at an early stage of development. Mechanisms of *co-creation*, learning evaluation, innovation adoption, and the intensity of knowledge exchange among stakeholders have not yet been systematically quantified. The available evidence therefore more strongly supports the emergence of a living-laboratory architecture than the conclusion that all of its functions have reached full maturity.

This distinction also differentiates the CoE from a conventional demonstration site. A demonstration site primarily communicates what has been implemented, whereas a *living laboratory* should enable stakeholders to observe, experiment, evaluate, learn from, and progressively improve existing practices. This distinction is fundamental to the future development of the model.

The Resulting Post-Mining Reclamation Center of Excellence Model

The synthesis of the findings resulted in a post-mining reclamation CoE model structured around four principal pillars: ecological restoration, circular economy, biodiversity conservation, and learning and replication. These pillars are not conceived as independent programs, but as interconnected components operating through resource flows, ecological processes, empirical data, innovation, stakeholder engagement, and continuous learning.

Table 4. Synthesis of the components of the post-mining reclamation Center of Excellence model

Component	Implementation evidence	Function within the CoE model
Ecological restoration	126.26 ha revegetated; 332,151 plants	Ecosystem foundation and reclamation demonstration
Circular economy	Litter + livestock manure + sawdust → compost blocks	Biological resource recirculation
Biodiversity conservation	21 vegetation species	Habitat baseline and foundation for biodiversity monitoring
Innovation	Production, characterization, and field application of compost blocks	Environmental technology demonstration
Learning	Technical data, field practices, testing, and documentation	Foundation for the <i>living laboratory</i>
Stakeholders	Company, site managers, communities, farmers/livestock farmers	Collaboration and knowledge transfer
Replication	Documentable and adaptable practices	Potential transfer of the model to other sites

The model indicates that interactions among the four pillars occur through at least three complementary circular mechanisms. The first is resource circularity. Reclamation vegetation generates biomass; the biomass is recovered and transformed into compost blocks; and the resulting product is reintegrated into planting activities. This mechanism links ecological restoration with circular economy principles and demonstrates that outputs generated through reclamation can subsequently become inputs for further site management.

The second is ecological circularity. Revegetation establishes vegetation structure that generates biomass while potentially strengthening habitat conditions and ecosystem functions. The development of these functions can, in turn, provide a basis for biodiversity conservation and the longer-term sustainability of the reclaimed ecosystem. At the current stage, however, this mechanism should be regarded as a developmental framework because the available biodiversity data constitute a vegetation baseline rather than longitudinal evidence of community-level ecological change.

The third is knowledge circularity. Field implementation generates empirical data and practical experience; these are evaluated and documented; the resulting evidence supports learning; and the learning process informs improvements in subsequent implementation and provides a basis for replication. Monitoring and evaluation therefore do not constitute the terminal stage of the program but instead function as a feedback loop supporting adaptive management.

These three mechanisms are interconnected through stakeholder engagement and adaptive monitoring. The resulting CoE is therefore inherently non-linear: changes in one component can generate feedback across other components. For example, vegetation development produces biomass for circular utilization; biomass processing generates innovations that can be reintegrated into planting; innovation implementation produces data; and these data subsequently become learning resources for refining future management practices.



Figure 6. The resulting post-mining reclamation Center of Excellence model

The conceptual novelty of the model becomes particularly evident at this level of integration. Its novelty does not reside in reclamation, compost-block technology, biodiversity conservation, or learning activities considered individually, as each is already recognized within environmental management practice. Rather, it's added value lies in the integration of resource circularity, ecological processes, and knowledge circulation within a unified and adaptive post-mining management system. The four pillars define the structural architecture of the model, while the three circular mechanisms explain its functional dynamics.

This finding extends the perspective proposed by Measham et al. (2024), who argued that post-mining transitions should move beyond technical closure toward the creation of broader and enduring post-mining values and functions. Within the model developed here,

these values emerge through the transformation of reclaimed landscapes from objects of environmental recovery into platforms that connect ecological recovery, resource recovery, knowledge generation, and adaptive management.

Accordingly, the resulting CoE can be operationally defined as: a living-laboratory-based post-mining reclamation management system that integrates ecological restoration, biological resource circularity, biodiversity conservation, and learning and replication through stakeholder engagement and adaptive monitoring.

This operational definition is important because it establishes a clearer conceptual boundary for the CoE proposed in this study. The CoE is not merely a center, facility, or collection of environmental programs; rather, it represents an integrative mechanism through which a reclaimed landscape can continuously generate ecological functions, innovation, empirical evidence, knowledge, and improvements in management practice.

Implications and Future Development of the Model

The resulting model has important implications for how post-mining reclamation performance is conceptualized. Conventional approaches tend to frame reclamation as a predominantly linear sequence: landform preparation → revegetation → maintenance → target achievement. The CoE model extends this sequence into a more adaptive system: reclamation → ecological recovery → resource utilization → innovation → monitoring → learning → improvement → replication.

This transition shifts the emphasis from compliance-oriented reclamation toward adaptive, knowledge-based post-mining management. The performance of a reclaimed landscape should therefore not be assessed exclusively on the basis of reclaimed area or vegetation establishment, but also on its capacity to sustain ecological functions, recover resource value, generate innovation, produce knowledge, and translate learning into improved management practices.

A second implication concerns the role of the circular economy within reclamation. The findings demonstrate that circularity can begin to emerge once reclaimed vegetation becomes established and starts generating biomass. Ecological recovery and circular economy should therefore not necessarily be regarded as separate management agendas. As the biological assets of a reclaimed landscape develop, opportunities for recovering and recirculating locally generated resources may also increase, provided that such utilization does not compromise the ecological functions of litter and natural nutrient cycling. This perspective creates opportunities for developing indicators that measure not only the quantity of recovered biomass but also the balance between *resource recovery* and the ecological requirements of the reclaimed ecosystem.

A third implication concerns the function of monitoring. Within the CoE model, monitoring is not merely a mechanism for demonstrating regulatory compliance or documenting program achievements; it becomes a learning mechanism. Data on vegetation, biodiversity, soil characteristics, biomass circularity, innovation performance, and stakeholder participation can be used to identify change, evaluate management practices, and determine subsequent interventions. The quality and maturity of the CoE will therefore ultimately depend on its capacity to transform data into management decisions.

The model also has implications for replication. Replication should not be interpreted as the direct duplication of the Temandang program at other sites. Ecological conditions, mining commodities, biomass availability, social structures, and post-mining priorities vary substantially among locations. What is more appropriately transferable is the

architecture of the model: identification of local assets, mapping of resource flows, integration of conservation practices, development of site-responsive innovations, monitoring, learning, and adaptive improvement.

In subsequent stages, CoE maturity could be evaluated through indicators representing ecological functionality, biodiversity, resource circularity, innovation performance, stakeholder engagement, knowledge generation and transfer, and the extent to which practices are successfully replicated or adapted. Longitudinal monitoring will be required to document objectively the transition from baseline conditions toward more mature stages of CoE development.

Within this framework, the CoE should not be regarded as a final status achieved once a predefined set of activities has been completed. Rather, it should be understood as an evolving adaptive management system sustained by interactions among ecosystems, resources, innovation, people, empirical evidence, and learning. This perspective provides the strategic foundation for transforming reclaimed post-mining landscapes from spaces of environmental recovery into *living laboratories* for environmental innovation, knowledge generation, and the continuous advancement of sustainable post-mining management.

CONCLUSION AND RECOMMENDATIONS

Conclusions

The development of the post-mining reclamation *Center of Excellence* (CoE) resulted in an integrated management model comprising four main pillars: ecological restoration, circular economy, biodiversity conservation, and learning and replication, within a *living laboratory* framework. The model was developed based on existing reclamation assets and strengthened through the utilization of local biomass for compost blocks, thereby establishing a biological cycle of vegetation–litter–biomass processing–compost blocks–planting–vegetation.

The novelty of the model lies in the integration of reclamation practices, biological resource circularity, biodiversity conservation, innovation, and learning within a unified site management system. Through this approach, the reclaimed post-mining area serves not only as an environmental restoration site but also as a platform for demonstration, innovation, learning, and the development of sustainable reclamation practices.

Recommendations

Further development of the CoE should focus on strengthening data-driven monitoring and evaluation systems, particularly for ecosystem recovery, biodiversity, biomass circularity, and the performance of compost block innovations. Future testing of compost blocks should include control or comparison groups and longer observation periods to quantitatively assess their effectiveness.

Community and stakeholder engagement should also be strengthened through training, mentoring, and knowledge transfer supported by measurable performance indicators. Furthermore, CoE best practices should be systematically documented and standardized to support learning and replication of the model in other post-mining areas.

DAFTAR PUSTAKA

- Campbell, T., Dixon, K. W., Bradshaw, S. D., Gann, G. D., Hartley, W., Lambers, H., & Wardell-Johnson, G. (2024). Standards-based evaluation inform ecological restoration outcomes for a major mining activity in a global biodiversity hotspot. *Restoration Ecology*, 32(8), e14236. <https://doi.org/10.1111/rec.14236>
- Cotrino-Teatino, M. A., & Marquina-Araujo, J. J. (2025). Circular economy in the mining industry: A bibliometric and systematic literature review. *Resources Policy*, 102, 105513. <https://doi.org/10.1016/j.resourpol.2025.105513>
- Favretto, N., Stringer, L. C., Dougill, A. J., & Kruger, L. (2022). Knowledge exchange enhances engagement in ecological restoration and rehabilitation initiatives. *Restoration Ecology*, 30(2), e13565. <https://doi.org/10.1111/rec.13565>
- Gastauer, M., Pinheiro, T., Caldeira, C. F., Ramos, S. J., Coelho, R. R., Fonseca, D. S., Tyski, L., Cardoso, A. L. R., Carvalho Neto, C. S., Guimarães, L., & Sarmiento, P. S. M. (2024). Large-scale forest restoration generates comprehensive biodiversity gains in an Amazonian mining site. *Journal of Cleaner Production*, 443, 140959. <https://doi.org/10.1016/j.jclepro.2024.140959>
- Hadfield, P., Prescott, M., Holden, J., Novalia, W., Suwarso, R., Marthanty, D. R., Priadi, C., Kirana, K. H., Endyana, C., Hardesty, B. D., Taufik, F. D., Zurbrugg, C., Josey, B., Astuti, N., Wong, T. H. F., Ramirez-Lovering, D., & Raven, R. (2024). Citarum Living Lab: Co-creating visions for sustainable river revitalisation. *PLOS Water*, 3(8), e0000200. <https://doi.org/10.1371/journal.pwat.0000200>
- Harries, K. L., Woinarski, J., Rumpff, L., Gardener, M., & Erskine, P. D. (2024). Characteristics and gaps in the assessment of progress in mine restoration: Insights from five decades of published literature relating to native ecosystem restoration after mining. *Restoration Ecology*, 32(1), e14016. <https://doi.org/10.1111/rec.14016>
- Hernández-Santín, L., Gagen, E. J., & Erskine, P. D. (2024). Setting restorative goals with a regional outlook: Mine-rehabilitation outcomes influence landscape connectivity. *Journal of Environmental Management*, 357, 120778. <https://doi.org/10.1016/j.jenvman.2024.120778>
- Iskandar, I., Suryaningtyas, D. T., Baskoro, D. P. T., Budi, S. W., Gozali, I., Saridi, Masyhuri, & Dultz, S. (2022). The regulatory role of mine soil properties in the growth of revegetation plants in the post-mine landscape of East Kalimantan. *Ecological Indicators*, 139, 108877. <https://doi.org/10.1016/j.ecolind.2022.108877>
- Measham, T., Walker, J., Haslam McKenzie, F., Kirby, J., Williams, C., D'Urso, J., Littleboy, A., Samper, A., Rey, R., Maybee, B., Brereton, D., & Boggs, G. (2024). Beyond closure: A literature review and research agenda for post-mining transitions. *Resources Policy*, 90, 104859. <https://doi.org/10.1016/j.resourpol.2024.104859>
- Navarro-Ramos, S. E., Sparacino, J., Rodríguez, J. M., Filippini, E., Marsal-Castillo, B. E., García-Cannata, L., Renison, D., & Torres, R. C. (2022). Active revegetation after mining: What is the contribution of peer-reviewed studies? *Heliyon*, 8, e09179. <https://doi.org/10.1016/j.heliyon.2022.e09179>
- Pavloudakis, F., Roumpos, C., & Spanidis, P.-M. (2024). Planning the closure of surface coal mines based on circular economy principles. *Circular Economy and Sustainability*, 4, 75–96. <https://doi.org/10.1007/s43615-023-00278-x>
- Pratiwi, Narendra, B. H., Siregar, C. A., Turjaman, M., Hidayat, A., Rachmat, H. H., Mulyanto, B., Suwardi, Iskandar, Maharani, R., Rayadin, Y., Prayudyaningsih, R., Yuwati, T. W., Prematuri, R., & Susilowati, A. (2021). Managing and reforesting

- degraded post-mining landscape in Indonesia: A review. *Land*, 10(6), 658. <https://doi.org/10.3390/land10060658>
- Rodríguez-Berbel, N., Soria, R., Ortega, R., Lucas-Borja, M. E., & Miralles, I. (2022). Benefits of applying organic amendments from recycled wastes for fungal community growth in restored soils of a limestone quarry in a semiarid environment. *Science of the Total Environment*, 806, 151226. <https://doi.org/10.1016/j.scitotenv.2021.151226>
- Soria, R., Ortega, R., Bastida, F., & Miralles, I. (2021). Role of organic amendment application on soil quality, functionality and greenhouse emission in a limestone quarry from semiarid ecosystems. *Applied Soil Ecology*, 164, 103925. <https://doi.org/10.1016/j.apsoil.2021.103925>
- Tibbett, M. (2024). Post-mining ecosystem reconstruction. *Current Biology*, 34(9), R387–R393. <https://doi.org/10.1016/j.cub.2024.03.065>
- Worden, S., Svobodova, K., Côte, C., & Bolz, P. (2024). Regional post-mining land use assessment: An interdisciplinary and multi-stakeholder approach. *Resources Policy*, 89, 104680. <https://doi.org/10.1016/j.resourpol.2024.104680>
- Young, R. E., Gann, G. D., Walder, B., Liu, J., Cui, W., Newton, V., Nelson, C. R., Tashe, N., Jasper, D., Silveira, F. A. O., Carrick, P. J., Hägglund, T., Carlsén, S., & Dixon, K. W. (2022). International principles and standards for the ecological restoration and recovery of mine sites. *Restoration Ecology*, 30(S2), e13771. <https://doi.org/10.1111/rec.13771>
- Yuan, C., Wu, F., Wu, Q., Fornara, D. A., Heděnc, P., Peng, Y., Zhu, G., Zhao, Z., & Yue, K. (2023). Vegetation restoration effects on soil carbon and nutrient concentrations and enzymatic activities in post-mining lands are mediated by mine type, climate, and former soil properties. *Science of the Total Environment*, 879, 163059. <https://doi.org/10.1016/j.scitotenv.2023.163059>
- Zhu, Y., Wang, L., Ma, J., Hua, Z., Yang, Y., & Chen, F. (2024). Assessment of carbon sequestration potential of mining areas under ecological restoration in China. *Science of the Total Environment*, 921, 171179. <https://doi.org/10.1016/j.scitotenv.2024.171179>