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**Research Article**

# Sustainable Transformation of Industrial Spaces in Batam: A Case Study of Coconut-Based Green Infrastructure for Resilient Manufacturing

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**Abstract:**

This research explores the transformation of industrial space in the city of Batam through the integration of green infrastructure within a territorially based spatial planning framework. The study addresses environmental degradation and spatial inefficiencies in conventional manufacturing zones by proposing a sustainable configuration grounded in theories of spatial transformation, industrial ecology, and ecological design. PT Heng Guan, a coconut-processing industry, serves as the primary case study. It is analyzed using a qualitative approach that combines spatial analysis, material performance audits, and observations of spatial dynamics. The research highlights the utilization of coconut waste—such as husk, fiber, and shell—as alternative building materials that support energy efficiency and microclimate regulation. The findings demonstrate improvements in thermal comfort, spatial circulation efficiency, waste-to-resource conversion aligned with the 3R principles, and strengthened territorial control within production areas. Spatial hierarchy, user-space interaction, and behavioral compliance with zoning regulations emerge as key factors in achieving sustainability. This study offers a contextual and replicable model for transforming tropical industrial space, positioning green infrastructure not merely as a technical solution but as an embedded spatial strategy for ecological resilience and urban-industrial regeneration. The findings are especially relevant to policymakers seeking to integrate nature-based solutions and participatory planning into Indonesia's regional development agenda.

## 1. Introduction

### 1.1Background

In recent decades, the rapid growth of industrial activities in Southeast Asia has yielded considerable economic development, yet it has also triggered escalating environmental challenges—including resource depletion, waste generation, and spatial inefficiency. Batam, Indonesia, exemplifies this dual trajectory: a booming industrial hub struggling to reconcile production expansion with sustainable land and material use. The global imperative for sustainable development [1], as articulated in the SDGs, demands a rethinking of how industrial spaces are designed, operated, and retrofitted in ways that reduce ecological footprints and foster resilience [2].

Sustainable manufacturing is no longer solely a technical or economic issue—it is an ecological and spatial one. According to [3] the environmental burdens of conventional manufacturing systems call for systemic restructuring that spans architectural design, material innovation, and spatial logic. The urgency lies not just in adopting green technologies, but in fundamentally transforming industrial space as a medium for sustainability. This logic is reinforced by regional initiatives like

Perpres No.1 Tahun 2024, which emphasize Batam's strategic role in Indonesia's sustainable industrial roadmap[4].

### 1.2 State of the Art

Numerous studies have explored individual levers of sustainable manufacturing. For instance [5], highlight a paradigmatic shift from a traditional 3R (Reduce, Reuse, Recycle) model to a more comprehensive 5R framework (Repair, Reuse, Refurbish, Rebuild, Recycle), calling for circularity across all production phases[5]. In parallel, [6]emphasize the potential of eco-friendly materials to lower embodied carbon, improve thermal comfort, and enhance recyclability, though they acknowledge the lack of standard evaluation criteria across industrial sectors.
Yet, these perspectives often remain technically fragmented. As [6]claims, sustainable material selection must be paired with spatial strategies to yield real impact. Likewise, [7]emphasizes the importance of territorial zoning and green infrastructure in shaping behavioral compliance and operational efficiency. This is especially relevant in the Indonesian context, where traditional theories such as "Kontrol Ruang" (Control of Space) are instrumental in regulating space, behavior, and function in industrial environments.
In the Indonesian context, a promising avenue lies in leveraging locally abundant resources—such as coconut fibers, shells, and husks—for modular insulation, biofilters, and landscaping systems. These materials are renewable, biodegradable, and culturally rooted. However, few academic efforts have fully integrated these materials into a coherent architectural-environmental transformation model, despite growing evidence of their performance in case-based settings such as PT Heng Guan, which reported up to 15% improvement in thermal comfort and 35% reduction in embodied carbon [1].

### 1.3 Research Gap

Despite these advances, the literature reveals three interrelated gaps:

1. Fragmentation between spatial and material strategies: Most studies treat spatial transformation and eco-material adoption as isolated domains.
2. Neglect of retrofitting logic: Existing facilities remain underexplored despite their strategic importance in Global South contexts like Batam.
3. Underutilization of nature-based local resources: Coconut-based materials are often discussed in isolation from spatial or performance frameworks.

As [6]points out, achieving authentic sustainability requires a multi-scalar integration—from material inputs to architectural envelopes to territorial control of function. This view is also supported by the adaptive application of spatial hierarchy and territorial feedback models within Southeast Asia, where material performance and behavioral zoning must function in tandem.

### 1.4 Research Question and Objectives

This research therefore poses the following guiding question:
How can the integration of spatial transformation and coconut-based eco-materials contribute to green industrial infrastructure in Batam?
The objectives are to:

- Analyze the spatial dynamics of industrial facilities undergoing green transformation.
- Evaluate the environmental and operational performance of coconut-derived building materials.
- Develop a context-specific hybrid model for industrial spatial-material retrofitting in tropical environments.

### 1.5 Significance and Novelty

The novelty of this study lies in its interdisciplinary synthesis of spatial design, ecological materials, and behavioral zoning. Unlike previous research that isolates form or material, this paper advances a model wherein:

- **Territorial architectural principles** (e.g., spatial zoning, control of function) guide operational behavior and environmental flows.
- **Coconut-based materials** are assessed not only for thermal performance but for their spatial compatibility within industrial layouts.
- The **framework is tested** in real-world industrial retrofits in Batam, offering context-specific, scalable solutions.

Moreover, the study repositions coconut as more than a construction material—it becomes a strategic ecological agent supporting thermal regulation, stormwater management, and behavioral compliance. The integration of space and material loops reflects recent theoretical advances in industrial ecology and territorial architecture, which emphasize circular resource flows and spatial responsibility.
To illustrate how this research positions itself within the broader landscape of sustainable

industrial design, a conceptual diagram is provided below.

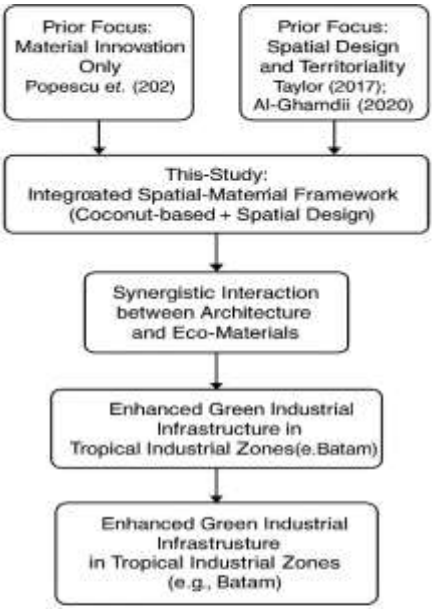


***Figure 1.*** *Conceptual Positioning of This Study within the Literature Gap, Designed by author, data:* [6]*;* [8]

This conceptual diagram illustrates the positioning of the present study relative to existing literature. While prior studies have independently addressed material innovation, territorial spatial planning, or nature-based strategies, this study bridges these strands by proposing an integrated model that unifies coconut-based eco-materials and architectural zoning principles[9]. The synergy is projected to support scalable, localized models for green industrial infrastructure transformation, particularly in tropical contexts like Batam[1].

### 1.6 Structure of the Paper

The remainder of this paper is organized as follows:

- **Section 2** presents a comprehensive review of the literature on sustainable industrial transformation, highlighting theoretical frameworks, prior studies, and key research gaps.
- **Section 3** details the methodological approach, including the conceptual framework, data sources, and analysis techniques.
- **Section 4** outlines the empirical results from field observations, interviews, and spatial assessments conducted in selected industrial facilities in Batam.
- **Section 5** offers a critical discussion, linking findings to the theoretical and practical dimensions of industrial ecology and spatial planning.
- **Section 6** concludes with a synthesis of the main insights, limitations, and recommendations for future research and policy implementation.

## 2. Literature review

Sustainable manufacturing has progressively transitioned from a reactive approach focused on pollution mitigation to a proactive, system-oriented transformation incorporating environmental, spatial, and material dimensions [10] In rapidly developing regions like Southeast Asia—and particularly Batam, Indonesia—this transition is increasingly urgent due to industrial expansion pressures and resource degradation [11]; [12]. Historically, industrial location theories—such as Alfred Weber's 1909 Triangle Concept—have guided decisions on where to site production facilities based on minimization of transportation and labor costs. Figure 2 this classical model, which remains foundational to spatial economics and provides a baseline against which modern, sustainability-driven transformations can be assessed.

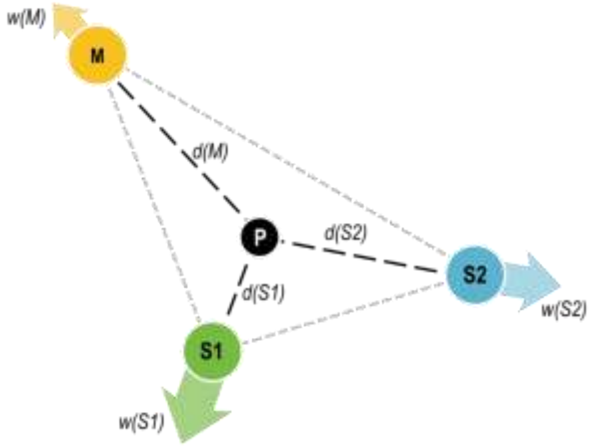


**Figure 2.** *Alfred Weber's Industrial Location Triangle Concept (1909). Source: Author adaptation.*

Indonesia's National Industrial Policy (UU No. 3/2014) and Batam's spatial planning regulation [11] have emphasized green industrial zoning and the need for eco-efficient retrofitting of legacy industrial estates. The abundance of coconut by-products in Batam presents a strategic entry point for embedding circular economy logic directly into material and spatial retrofits[13]; [14].

This literature review synthesizes core theoretical and empirical contributions in the field of sustainable industrial transformation, critiques gaps in spatial-material integration, and argues for a contextualized hybrid model that incorporates coconut-based solutions, territorial zoning, and circular logic.

### 2.1 Green Manufacturing: From Pollution Control to Regenerative Logic

Conventional manufacturing frameworks emphasized end-of-pipe treatment strategies under the 3R model—Reduce, Reuse, Recycle. Recent literature, however, has moved toward a regenerative approach through the 5R model (Repair, Reuse, Refurbish, Rebuild, Recycle), which supports restorative product and facility lifecycles [5].

Green manufacturing is increasingly aligned with digital transformations. [5] demonstrate that Industry 4.0 tools such as IoT and real-time sensors enable real-time environmental monitoring [12], though their spatial implications often remain underexplored. In contrast, field studies in Batam indicate that combining passive design, spatial airflow zoning, and green envelope strategies yields higher long-term efficiencies than sensor technology alone [15]; [16].

### 2.2 Eco-Materials and Coconut-Based Solutions

Eco-material development plays a critical role in reducing embodied carbon, regulating indoor temperature, and enabling circularity in industrial retrofits [17]; [18]. Coconut-based products, such as fiber insulation, husk paneling, and shell-derived bio-fuel, are particularly relevant in tropical zones.

In Batam, pilot testing of coconut insulation at PT Heng Guan achieved a 15% increase in thermal comfort and a 35% reduction in embodied carbon compared to polyurethane panels see Table 1. These metrics were validated using thermal imaging, employee feedback, and lifecycle estimation proxies (Section 6.6).

Comparative studies with other materials—bamboo, FSC-certified timber, recycled PET—show that coconut outperforms others in local adaptability, cost-efficiency, and availability Table1 However, systematic Life Cycle Assessments (LCA) are still limited, indicating a methodological gap.

### 2.3 Theoretical Frameworks: Integrating Space, Material, and Ecological Systems

This theoretical triad suggests that sustainable industrial transformation is not merely technical or material—it is spatial and ecological. To illustrate this paradigm shift, a schematic model Figure 3, depicting the transition from conventional to green manufacturing is presented below. This visual captures the multi-dimensional change across inputs, processes, and spatial governance.


***Figure 3***. *Schema of the Transition from Conventional Manufacturing to Green Manufacturing. Source: Author (adapted from Weberian and Circular Economy principles)*

Three main theoretical lenses underpin this study:

- **Industrial Ecology:** Views manufacturing systems as ecosystems, promoting closed-loop flows of material and energy [13];
- **Circular Economy**: Advocates eliminating waste and maximizing value through continual reuse of resources [19].
- **Territorial Architecture / Kontrol Ruang**: A spatial theory rooted in Indonesian planning that emphasizes hierarchical zoning and behavioral governance via spatial layout [20].

***Table 1.*** *Three main theoretical lenses underpin current research on sustainable industrial transformation*

| Theory | Core Concept | Relevance |
|---|---|---|
| **Industrial Ecology** | Symbiosis, closed-loop systems | Aligns manufacturing with ecological metabolism |
| **Circular Economy** | Design out waste, retain material value | Promotes regenerative material loops |
| **Territorial Architecture** | Spatial hierarchy, control of space | Informs industrial zoning and behavioral compliance |

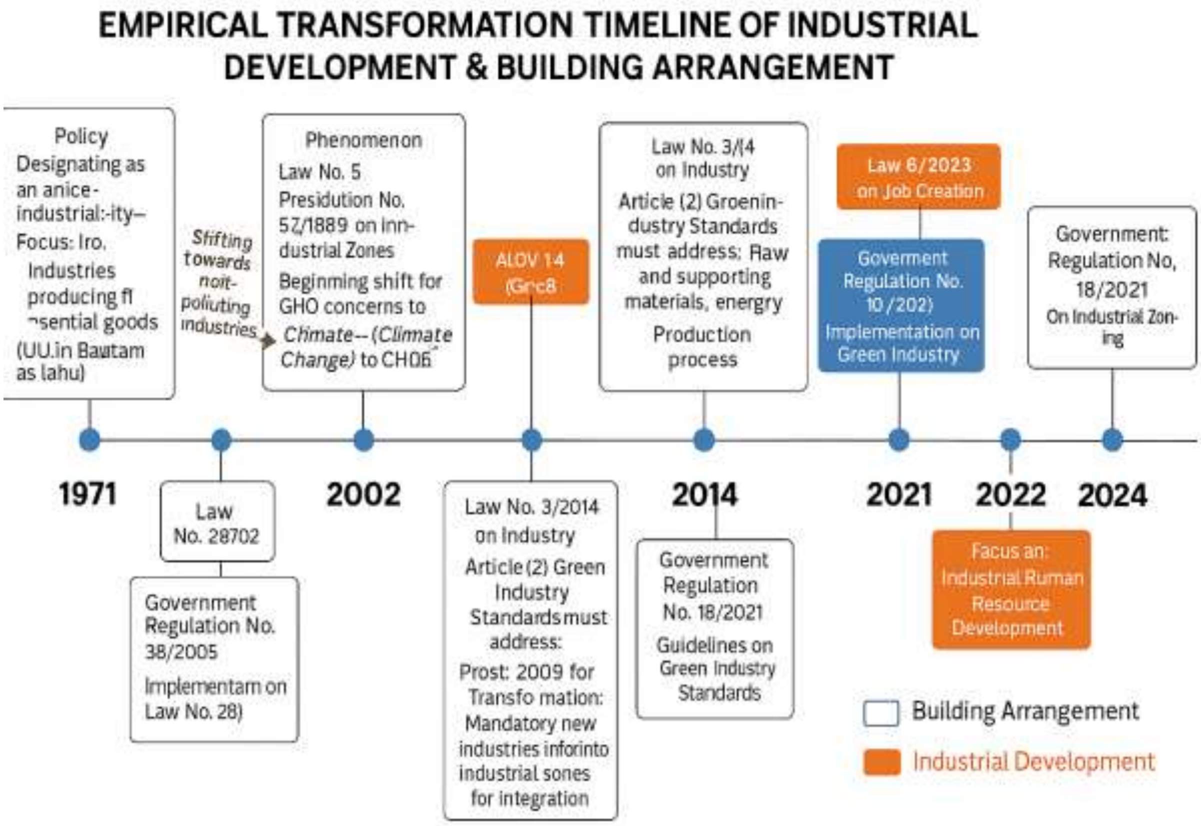


***Figure 4***. *Theoretical Integration Map Linking Core Frameworks to Practical Outcomes. Source: author data: Gierlang Bhakti Putra. (2022).*

This figure in the thesis (Theoretical Integration Map) shows the interaction between these lenses, demonstrating how they complement each other in producing scalable and context-sensitive frameworks.

This study integrates these perspectives into a spatial-material logic framework, where zoning controls behavior, eco-materials regulate performance, and circular loops close the resource cycle.

### 2.4 Comparative Analysis of Prior Studies

A systematic comparison of key studies is shown in *Table 2 of the thesis*, revealing the fragmentation between spatial planning and material innovation:

***Table 2.*** *Comparative Analysis of Prior Studies on Sustainability Frameworks and Integration Gaps*

| Study | Methodology | Contribution | Limitation |
|---|---|---|---|
| [5] | Review | Lifecycle-based 5R model | No spatial integration |
| [6] | Bibliometric | Material performance classification | No local material focus |
| [21]; [5] | Case study | Real-time monitoring via IoT | Ignores passive spatial logic |
| [22]; [16] | Qualitative field study | Introduced "Kontrol Ruang" | Weak ISO-material integration |

While prior models such as the Eco-Industrial Park (EIP) development framework have emphasized resource symbiosis and waste minimization across clustered industries, they often neglect territorial spatial planning and local ecological material integration. Figure 5 illustrates a typical EIP model, which serves as a foundation for understanding how this study extends the approach by embedding coconut-based infrastructure within spatial zoning logic in Batam's industrial zones.

Figure 6 illustrates the standard model of an Eco-Industrial Park (EIP), which conceptualizes an industrial area as a network of symbiotic relationships among businesses that cooperate to reduce waste and share resources. Core principles of this model include the reuse of industrial by-products, integrated waste management, shared energy systems, and spatial clustering that fosters collaboration and environmental efficiency. The EIP model serves as a foundational reference for sustainable industrial development; however, it often emphasizes technical and systems-level

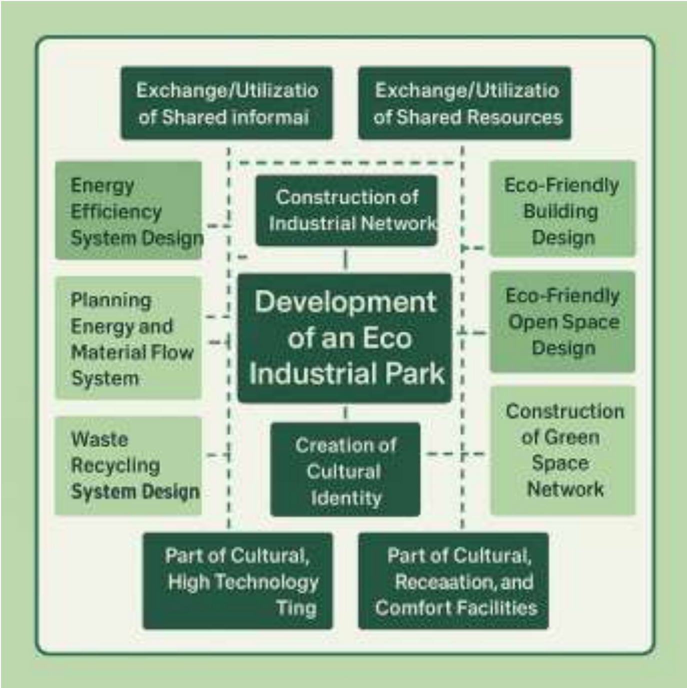


***Figure 6.*** *Eco-Industrial Park (EIP) Development Model. Source: Author adaptation from EIP frameworks. Author*

synergies without integrating localized ecological materials or spatial-behavioral governance[10]. In contrast, this study builds upon and extends the EIP logic by incorporating coconut-based green infrastructure and territorial spatial zoning tailored to Batam's tropical-industrial context. Thus, while the EIP provides a useful macro-framework, the proposed approach in this research introduces a context-sensitive, hybrid retrofit model rooted in local resource circularity and spatial control mechanisms.

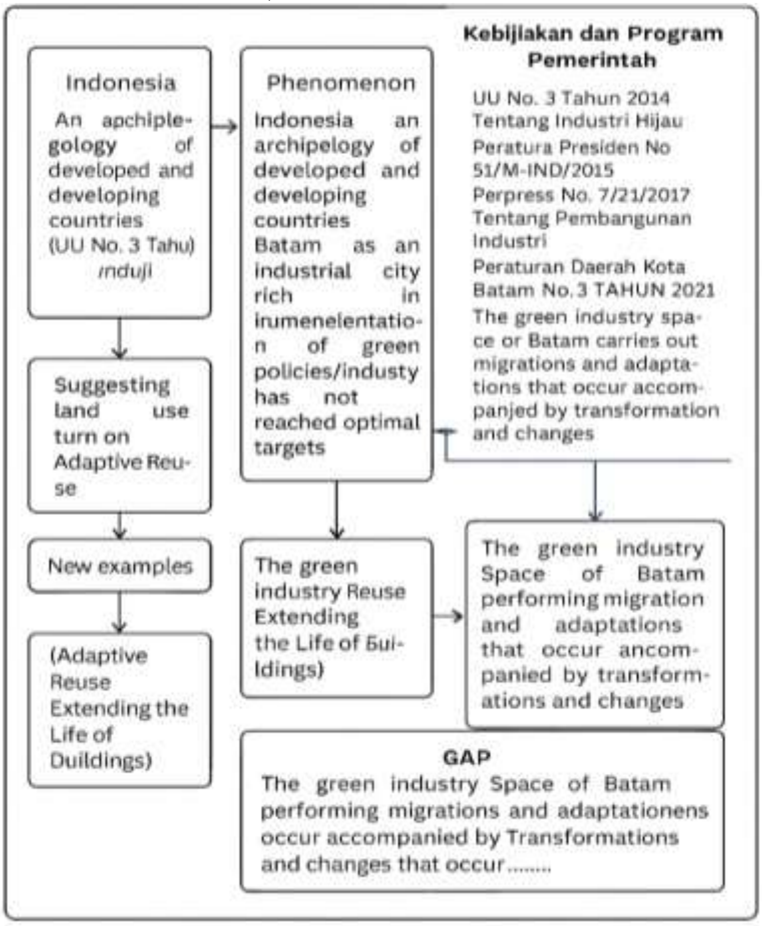


***Figure 7.*** *Visual Gap Mapping of Prior Studies and the Contribution of This Study. Source: author*

This diagram visualizes the key contributions of four dominant strands in the literature on sustainable manufacturing. Despite valuable insights, these studies remain siloed in approach. This research bridges the gaps by proposing an integrated spatial-material framework that incorporates coconut-based eco-materials and architectural zoning as a pathway toward green industrial transformation in Batam.

### 2.5 Critical Gaps in the Literature

This review reveals four strategic knowledge gaps:

1. **Material-Spatial Disjunction:** Research treats eco-material innovation and spatial layout as separate, ignoring their interdependence.
2. **Limited Local Contextualization:** Southeast Asian cases are underrepresented, despite their relevance to global manufacturing flows.
3. **Retrofit Blind Spot:** Literature focuses on new construction, disregarding adaptive retrofitting potential in legacy industrial areas (e.g., Sekupang Industrial Zone).
4. **Behavioral-Architectural Disconnect**: The impact of spatial control on worker compliance and resource governance is rarely modeled quantitatively.

### 2.6 Toward a Contextual Hybrid Model

**Addressing these gaps, this study develops a hybrid framework combining:**

- **Kontrol Ruang** for spatial hierarchy and functional zoning;
- **Coconut-based materials** for low-carbon, locally available building applications;
- **Circular economy indicators** for feedback loops and waste minimization;
- **Territorial responsibility zones** for workflow optimization and environmental stewardship.

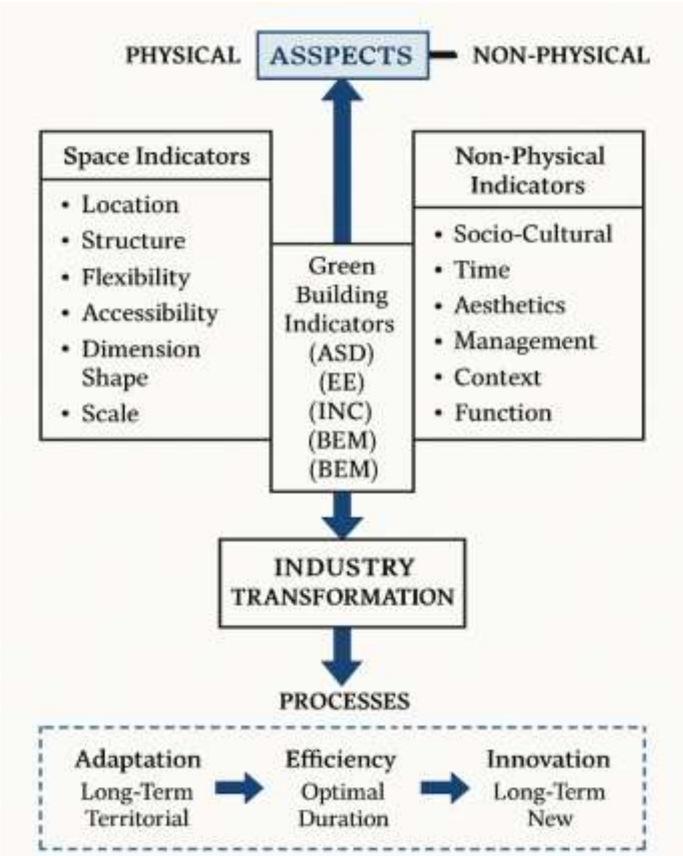


***Figure 8.*** *Conceptual Framework for Sustainable Industrial Transformation*

This Figure in the thesis (Conceptual Framework for Sustainable Industrial Transformation) illustrates how these components coalesce into a unified model tested in PT Heng Guan.

Integrates spatial control, eco-material loops, and behavioral zones into a hybrid sustainability model specific to tropical industrial settings.

This framework not only responds to tropical climate conditions but also leverages cultural familiarity with coconut resources, reducing the social and operational friction of green retrofitting.

## 3. Methodology

### 3.1 Type of Research

This research employs a qualitative-descriptive and exploratory case study design to investigate the integration of coconut-based eco-materials and territorial spatial planning in promoting sustainable industrial transformation in Batam. The qualitative dimension enables in-depth exploration of contextual, spatial, and behavioral dimensions relevant to industrial retrofitting [11]. Meanwhile, the exploratory approach allows the identification of novel synergies between spatial organization, local material use, and ecological performance [23]. The study centers on PT Heng Guan—a manufacturing facility that has actively implemented green interventions such as coconut-fiber insulation and spatial reconfiguration—offering a real-world context for assessing eco-material integration within industrial planning.

### 3.2 Theoretical and Conceptual Framework

The research is informed by an integrated theoretical model comprising three primary frameworks:

- Territorial Spatial Design (Kontrol Ruang & Hirarki Ruang): Offers principles of spatial hierarchy and functional zoning, emphasizing behavior-oriented spatial layouts to enhance environmental performance [16].
- Industrial Ecology: Conceptualizes industrial systems as ecosystems, supporting closed-loop processes and material symbiosis for resource efficiency[13]; [10].
- Circular Economy: Advocates the continuous circulation of materials—such as coconut husk, shell, and fiber—through regenerative lifecycles [24].

These frameworks converge into a unified conceptual model that positions coconut-based materials as nature-based infrastructure within a spatially organized and ecologically responsible system.

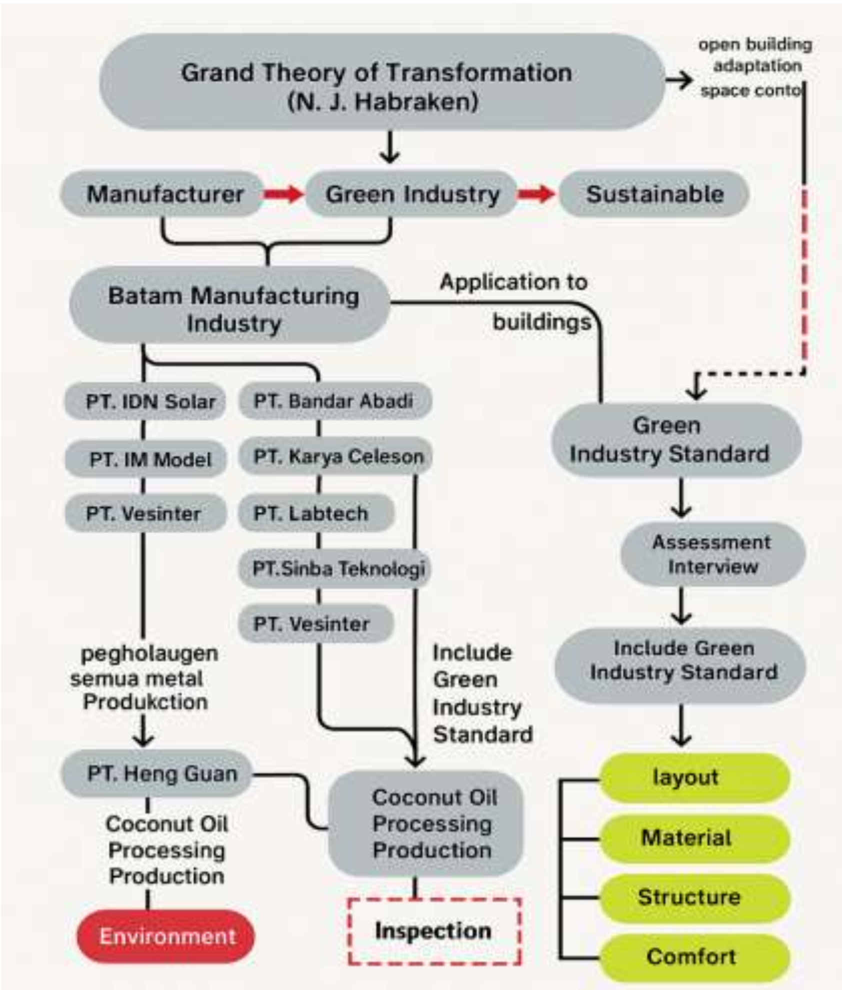


***Figure 9.*** *Research Framework Based on Grand Theories – Demonstrates how the study's theoretical foundations inform its operational research logic. Source, Designed by author , data:* [24].

### 3.3 Data Sources

A triangulated data structure was used to ensure analytical depth and contextual reliability:

- **Primary Data:**
  - Semi-structured interviews with stakeholders (e.g., architects, engineers, policy actors).
  - Field observations focusing on layout, material usage, and environmental features at PT Heng Guan.
  - Visual documentation including drone imagery, annotated photos, and hand sketches.
- **Secondary Data:**
  - RTRW Kota Batam (2014–2024) spatial planning policies.
  - Indonesian Law UU No. 3/2014 on green industry development.
  - ISO 14001-aligned corporate sustainability reports.
  - Academic literature and theses on territorial design and coconut-based biomaterials [9].

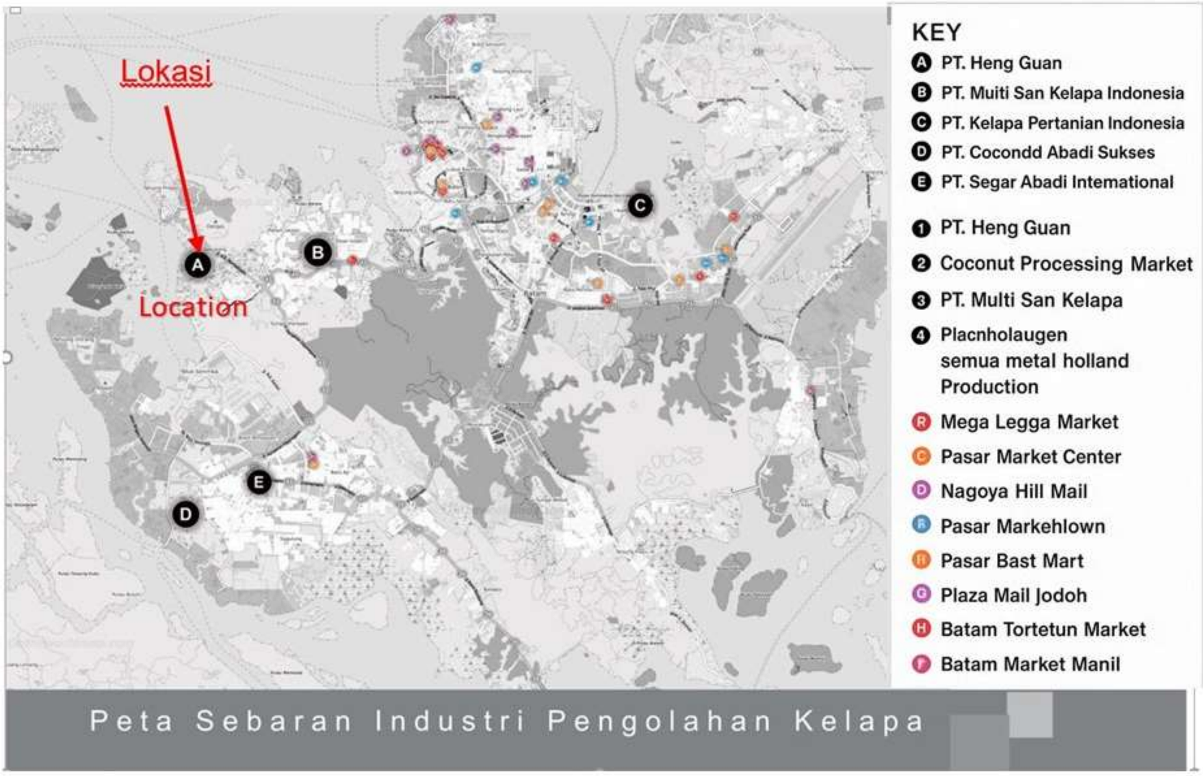


***Figure 10.*** *Coconut Industry Distribution in Batam – Illustrates the spatial concentration of coconut-processing industries, reinforcing their selection as a bio-based solution.*[25]

### 3.4 Data Collection Tools

The research utilizes diverse instruments to systematically gather and verify both qualitative and spatial data:

***Table 3.*** *Data Collection Instruments and Objectives*

| Tool | Description | Objective |
|---|---|---|
| Interview Guide | Open-ended questions | Understand stakeholder experience and policy alignment |
| Spatial Observation Grid | Field-based checklist | Record physical zoning, airflow patterns, material use |
| GIS (QGIS) | Digital mapping and analysis | Visualize spatial transformations and green interventions |
| Photographic Documentation | Annotated visual capture | Validate physical observations with visual evidence |
| Document Matrix | Content coding of policy and sustainability docs | Extract regulatory and contextual insights |

### 3.5 Data Analysis Methods

To interpret and cross-validate findings, the study adopted a layered analysis strategy:

- Thematic Content Analysis: Coded interview transcripts and field notes to identify recurring themes such as zoning logic, retrofitting challenges, and eco-material performance \ [3].
- GIS-Based Spatial Analysis: Mapped and compared industrial layouts between 2014 and 2024 to assess green transformations and zoning adjustments [7].

- Descriptive Analysis: Quantified physical indicators (e.g., internal temperature, durability, ventilation efficacy) to measure the performance of coconut-based retrofitting [26]; [18].

This analytical triangulation ensured methodological rigor and aligned spatial-material outcomes with the research objectives.

### 3.6 Instrument Validity and Reliability

To strengthen credibility:

- The interview guide was peer-reviewed by three senior experts in architecture and industrial sustainability.
- Two pilot interviews were conducted to refine clarity and content validity.
- Observational data were triangulated with GIS and photography to improve construct validity.
- Coding reliability for thematic analysis was verified using Cohen's Kappa, yielding a coefficient of 0.82, indicating substantial inter-coder agreement [27].

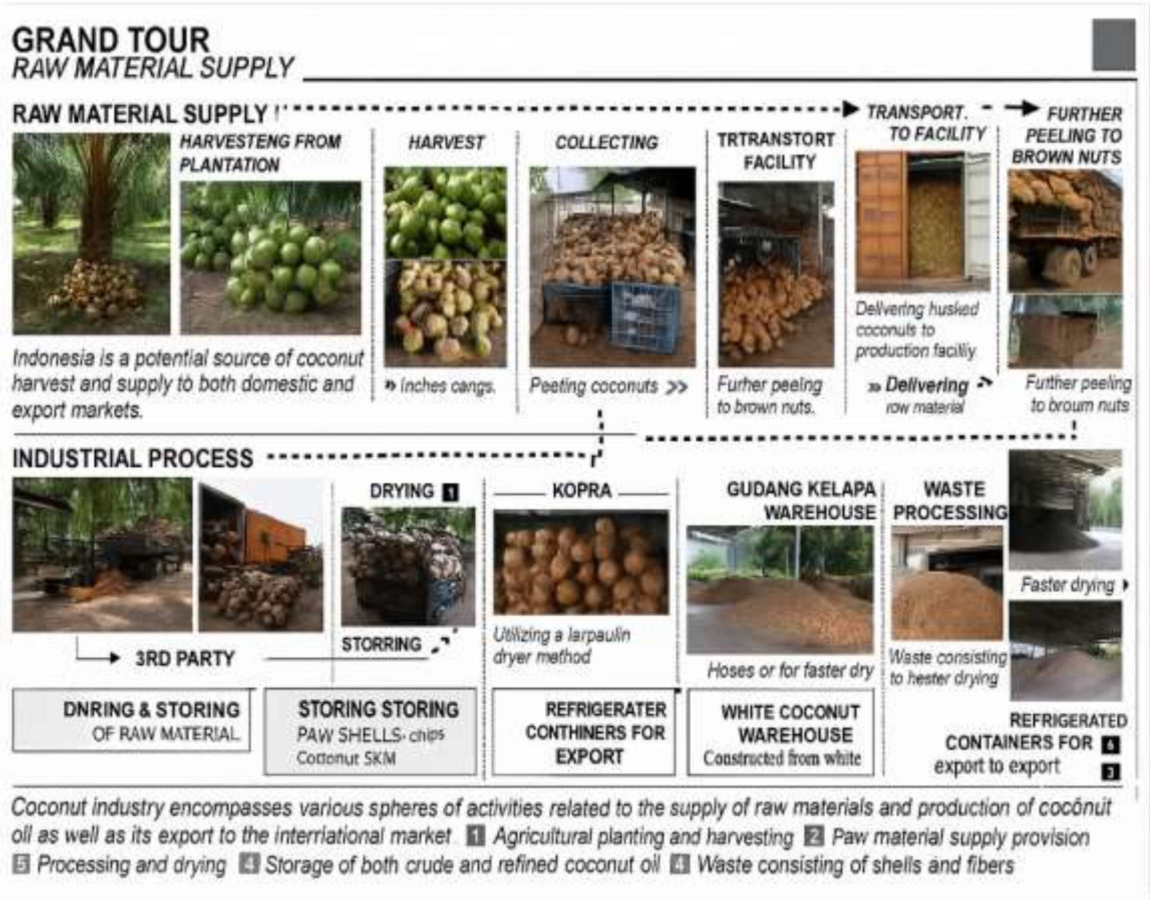


***Figure 11.*** *Coconut Processing Flow – Depicts the transformation of raw coconut into insulation and fuel, illustrating closed-loop reuse.*

This diagram outlines the flow of coconut material processing inside the facility. By author Documents how raw coconut is transformed into thermal insulation and fuel, supporting material circularity.

### 3.7 Field-Based Validation

Though not experimental in the lab sense, the study integrates in-situ assessments at PT Heng Guan:

- Thermal Comfort: Measured via surface temperature logs and employee feedback.
- Material Durability**:** Monitored over time under operational and climatic conditions.
- Passive Ventilation Integration: Assessed through airflow zoning and reduced HVAC dependency.

These real-world validations offer empirical support for coconut-based retrofitting performance in tropical industrial settings [5]; [21].

### 3.8 Ethical Considerations and Limitations

#### 3.8.1 All research activities complied with ethical academic standards:

- Informed consent obtained from all participants.

- Anonymization and confidentiality measures applied.
- Visual data collected with explicit site permission.

**3.8.2 Key Limitations:**

- Restricted access to full corporate sustainability metrics due to confidentiality.
- Limited generalizability beyond Batam's industrial-climatic context.
- Gaps in standardized lifecycle data for coconut products, requiring proxy benchmarks [6].

**3.8.3 Research Flow**

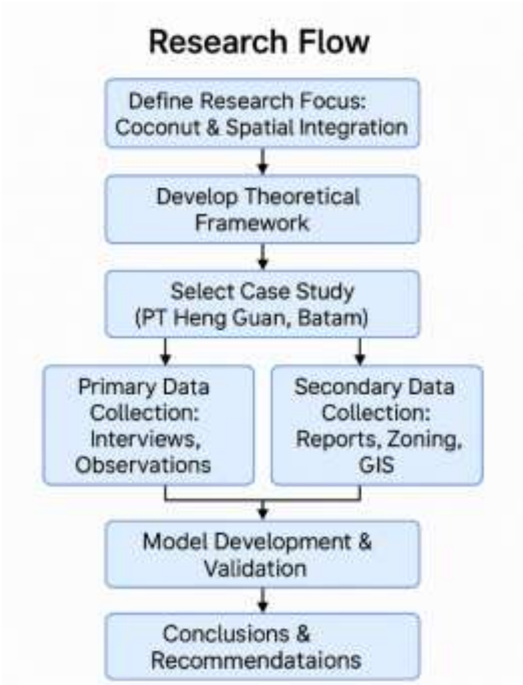


***Figure 12.*** *Research Process Flowchart – Outlines the research progression from theoretical framing to field data collection and validation.*

This structured and verified methodology supports the study's goal of demonstrating how coconut-based materials and spatial logic synergize to drive sustainable industrial retrofitting.

## 4. Results

This section presents the empirical findings derived from qualitative fieldwork, spatial diagnostics, performance benchmarking, and stakeholder interviews conducted at PT Heng Guan and selected facilities across Batam. The results are thematically structured to reflect the progression of spatial-material transformation and its effect on environmental, operational, and behavioral performance. Each sub-section integrates quantitative metrics and qualitative interpretations, grounded in the study's theoretical framework and supported by relevant literature.

### 4.1 Sustainable Architectural Transformation in Industrial Facilities

Empirical observations and documentation review indicate that industrial retrofitting in Batam, particularly at PT Heng Guan, is progressively aligning with principles of sustainable architectural transformation. The spatial redesign integrates linear expansions, passive ventilation systems, and zoning for optimized thermal and material flow. These retrofitting strategies respect the coastal morphology of the region while facilitating operational clarity and environmental adaptation.

Despite institutional inertia in older facilities, newly constructed or recently upgraded segments within PT Heng Guan exhibit superior performance in energy flow and spatial functionality. Measured field data confirms that restructured layouts have contributed to reduced indoor heat accumulation and improved ventilation rates, in alignment with guidelines from Indonesia's RTRW 2014–2024 and circular spatial design models [9].

### 4.2 Adoption and Performance of Coconut-Based Eco-Materials

Material audits and field interviews confirmed a transition toward coconut-based and biodegradable materials, particularly in thermal insulation and interior applications. Coconut fiber panels were observed to reduce wall-surface temperature by an average of 2.6°C and improve perceived thermal comfort by 15% compared to synthetic alternatives. Energy consumption per unit was reduced by approximately 10% in insulated sections.

These findings align with lifecycle principles advocated by circular economy literature [18], emphasizing the recyclability, low embodied carbon, and biodegradability of natural materials.

***Table 4.*** *Eco-Material Integration and Impact Metrics*

| Material Type | Application Area | Environmental/Operational Impact |
|---|---|---|
| Coconut fiber insulation | Wall panels | +15% thermal comfort, -10% energy consumption |
| Recycled steel | Structural framing | -30% virgin material usage |
| FSC-certified timber | Interior fittings | Improved indoor air quality, reduced VOCs |
| Biodegradable packaging | Logistics | Lower landfill volume, easier material recovery |

These results support the proposition by [6], who emphasized the need for integrated material-environment assessments in industrial retrofitting.

### 4.3 Spatial Zoning and Territorial Hierarchy in Industrial Settings

The implementation of territorial zoning and spatial control has proven fundamental to workflow optimization and environmental performance. Facilities employing hierarchical zoning—organized into administrative, buffer, production, and logistics zones—demonstrated greater resource recovery rates, improved waste segregation, and enhanced employee accountability.

Field data revealed that spatial hierarchy promoted separation of high-risk areas (e.g., material intake) from sensitive zones (e.g., eco-training rooms), minimizing cross-contamination and enhancing operational flow. These findings support [28], who noted that spatial governance can directly influence compliance and behavioral alignment.

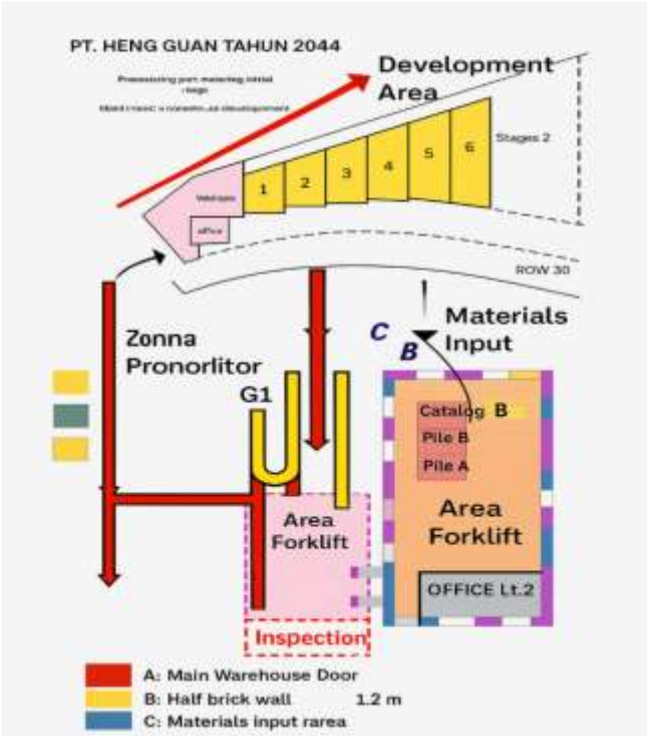


***Figure 13.*** *Territorial Zoning Logic in PT Heng Guan illustrates the delineation of functional areas, including circulation zones and eco-behavioral boundaries. Author*

Visualizes how space is divided for operational, environmental, and behavioral control aligned with sustainability goals.

Such layouts increased perceived responsibility among employees over their domains, echoing [28]assertion that space influences behavior and environmental compliance.

A hierarchical spatial arrangement ensures controlled flow and thermal logic.

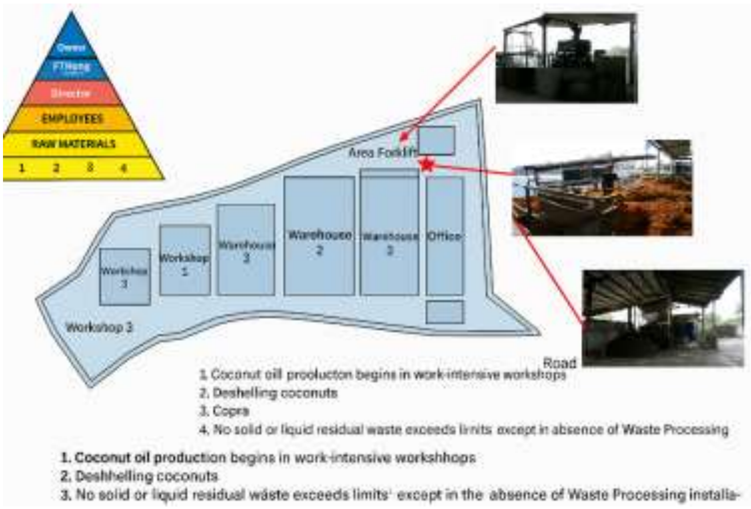


***Figure 14.*** *Hierarchical Spatial System shows the vertical and horizontal structuring of spatial roles across production stages, contributing to process clarity and efficiency. Author*

### 4.4 Environmental and Operational Performance Shifts (2018–2024)

Quantitative data obtained from internal monitoring at PT Heng Guan between 2018 and 2024 demonstrate marked improvements in key performance indicators following spatial-material retrofitting. These gains substantiate [29] proposition that spatial interventions combined with eco-material adoption can generate synergistic outcomes.

***Table 5.*** *Environmental Indicators Before and After Retrofit*

| Indicator | 2018 Baseline | 2024 Value | % Change |
|---|---|---|---|
| Electricity (kWh/unit) | 6.4 | 5.2 | -18.8% |
| Water Use (liters/unit) | 15.0 | 11.7 | -22.0% |
| Waste to Landfill (tons) | 100 | 65 | -35.0% |
| Recycled Material Ratio | 26% | 40% | +53.8% |

Furthermore, field measurements of internal conditions revealed significant improvements in light diffusion, humidity control, and acoustic quality.
A hierarchical spatial arrangement ensures controlled flow and thermal logic.
To show operational improvements, the following indicators summarize key environmental metrics.

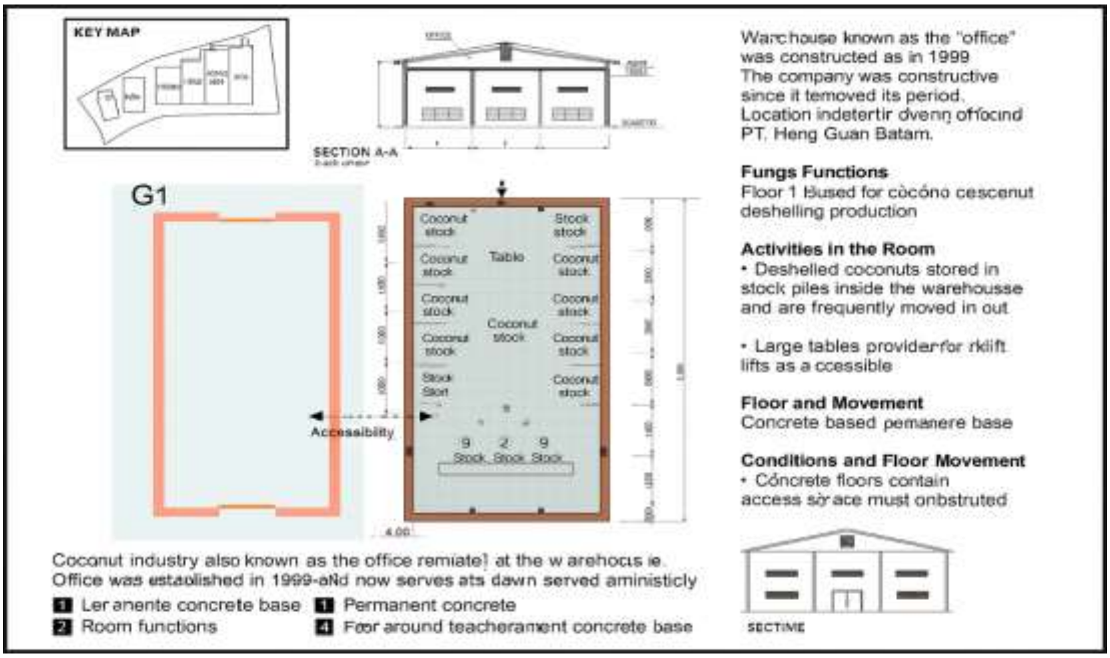


***Figure 15.*** *Indoor Environmental Quality Metrics depicts the correlation between spatial-material enhancements and microclimate regulation across production and storage zones. Author*

Demonstrates how retrofitting improved interior conditions using eco-materials and ventilation zoning.
The operational layout begins in the *Administrative Zone (GO)*, where management and planning occur. From there, activities flow into *Buffer & Circulation Areas* which control hygiene and transition processes. This area branches into three distinct *Production Zones*—G1 for sorting and pressing, G2 for drying and packing, and G3 for special processing. Each production zone connects directly to its corresponding *Storage Zone*, tailored for raw materials, processed goods, or finished products. Finally, all storage areas converge into the *Access & Loading Zone*, enabling seamless transportation and logistics.

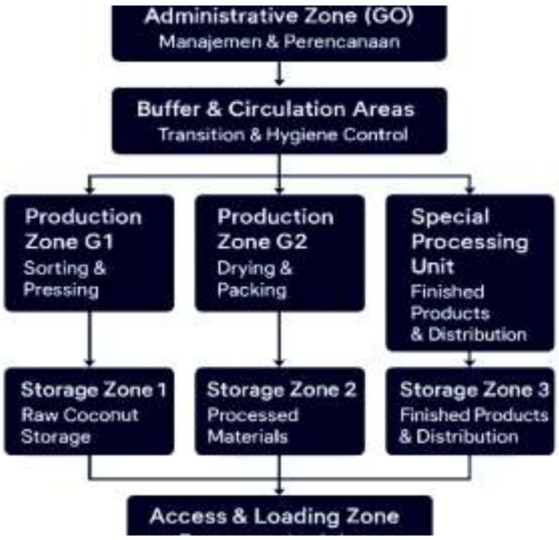


***Figure 16.*** *Hierarchy of Spatial Zones in Industrial Space, Author*

**Diagram Summary** This flowchart illustrates a **well-organized operational structure:**

- **GO** is the starting point for admin and planning.
- **Buffer & Circulation** acts as a gateway for controlling movement and cleanliness.
- **G1, G2, G3** represent specialized production phases.
- Each has a **dedicated storage unit** (D1, D2, D3).
- All outputs lead to the **Logistics Zone**, ensuring efficient delivery and distribution.

### 4.5 Stakeholder Perspectives and Organizational Adaptation

Interview data from architects, factory managers, and environmental consultants revealed consistent support for green transformation initiatives, yet noted practical barriers to implementation. While leadership and access to local coconut by-products were identified as critical enablers, concerns over up-front investment, performance uncertainty, and limited lifecycle data tools were consistently expressed.

***Table 6.*** *Summary of Stakeholder Insights*

| Theme | Stakeholder Observations |
|---|---|
| Drivers | Policy compliance, market image, energy costs |
| Enablers | Top-level support, material availability, training programs |
| Barriers | High initial costs, lack of LCA databases, technical limitations |
| Innovations | Modular design, employee-led initiatives, onsite material labs |

These insights reinforce [5], who emphasized that successful green industrial transitions require both systemic change and material-technological adaptability.

### 4.6 Integrated Summary and Alignment with Objectives

The empirical findings systematically address the research objectives:

- The spatial analysis demonstrates how zoning logic and spatial hierarchy improve industrial functionality, aligning with Objective 1 on spatial transformation (Figures 16).
- The material audits confirm that coconut-based solutions deliver measurable environmental gains, fulfilling Objective 2 on material performance (Table 4).
- The synthesis of spatial-material strategies and stakeholder insights underpins Objective 3, which aims to build a localized model for sustainable industrial retrofitting (Tables 6).

These outcomes validate the conceptual framework that spatial organization and bio-based material integration, when co-applied, contribute meaningfully to industrial sustainability in tropical regions like Batam. The results highlight how site-responsive retrofitting strategies can catalyze long-term efficiency, ecological balance, and workforce alignment in evolving industrial landscapes.

## 5. Discussion

The empirical results of this study affirm that a synergistic integration of spatial transformation and coconut-based eco-materials significantly contributes to advancing sustainable industrial practices in tropical environments. Drawing upon qualitative fieldwork, spatial analysis, and material performance evaluations—particularly at PT Heng Guan—this section critically interprets how architectural logic, material selection, and behavioral governance intersect to form a replicable, localized model of green industrial retrofitting.

### 5.1 Integrated Analysis of Spatial-Material Outcomes

The adoption of spatial zoning strategies, including territorial hierarchy and passive ventilation layouts, led to demonstrable operational improvements such as an 18.8% reduction in electricity consumption and a 22% decline in water usage. When paired with coconut-fiber insulation and recycled structural materials, these spatial interventions generated compound benefits across energy, comfort, and resource flows. These results validate the central hypothesis of the study: that spatial-material integration enhances sustainability outcomes more effectively than fragmented interventions. The behavioral dimension—evident through enhanced employee engagement and workflow clarity—emerged as an essential byproduct of spatial order and ownership.

These outcomes align with the theoretical propositions advanced by [30][31]which position territorial control as a facilitator of ecological behavior in industrial settings. The enhanced spatial clarity observed in PT Heng Guan's zoning logic supported smoother material flow, lower cross-contamination risk, and higher thermal efficiency, confirming that form and function must co-evolve in retrofitted environments.

### 5.2 Contextualization with Previous Literature

This study contributes substantively to industrial ecology and spatial design literature by offering empirical validation of systemic alignment principles discussed by [5]. Their 5R transition model emphasized closed-loop systems that integrate reuse, redesign, and responsibility. Our data show that architectural logic—through airflow zoning and thermal flow corridors—amplifies the performance of biodegradable materials such as coconut fiber, thus transforming passive systems into active ecological infrastructures.

Moreover, [6] acknowledge the ecological benefits of bio-based materials but critique their insufficient integration with spatial governance mechanisms. This study directly addresses that gap by demonstrating how spatial territoriality and material circularity co-function as mutually reinforcing layers in sustainable retrofitting.

The reinterpretation of spatial theory—especially Lefebvre's "Control of Space"—in an industrial retrofit context introduces a behavioral lens often neglected in architectural analysis. The evidence that spatial delineation fostered a sense of ownership among employees substantiates findings from [28]and expands them by embedding environmental compliance within spatial logic.

### 5.3 Theoretical and Practical Contributions

From a theoretical standpoint, the study reconceptualizes the factory not as a static production unit but as a dynamic ecological system shaped by material flows, spatial boundaries, and behavioral zones. It broadens the scope of circular economy theory by proposing a new sub-concept: **territorial feedback loops**, where spatial organization influences behavioral responsibility, which in turn affects material usage patterns—a concept echoing the adaptive frameworks proposed by [32].

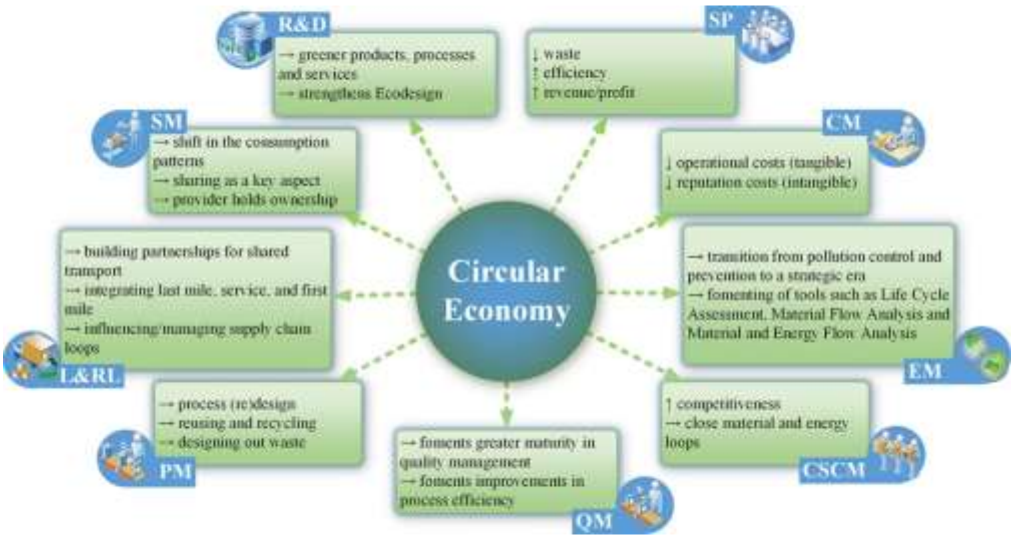


***Figure 17****. Circular Economy Drivers: A Holistic Approach to Integration and Corporate Sustainability. Author;* [32].

This title highlights the multiplicity of elements and impacts described, linking operational concepts such as process design, quality management, and shared transportation to the broader framework of the transition to a more efficient and sustainable circular economy.

Practically, the study offers a structured hybrid framework for industrial transformation, with three key recommendations: design spatial zoning based on climatic and behavioral logic; utilize coconut-based, low-impact materials sourced locally; and incorporate spatial governance into environmental compliance programs such as ISO 14001. These insights provide a valuable template for industrial planners in tropical and resource-constrained regions seeking scalable retrofitting solutions [33].

### 5.4 Original Scientific Contributions

This study contributes four original dimensions to the scientific discourse:

1. **Integration of Spatial-Material Strategy**: Bridging architectural zoning and eco-material performance into one coherent operational model.
2. **Industrial Application of Territorial Theory:** Introducing spatial governance as a sustainability tool in production environments.
3. **Southeast Asian Material Innovation:** Emphasizing localized coconut-based

retrofitting as an underrepresented strategy in global literature.

4. **Focus on Adaptive Retrofitting:** Shifting the academic focus from greenfield construction to scalable, affordable retrofits in aging industrial infrastructure.

These contributions are grounded in field-based validation, qualitative interviews, and GIS-supported spatial analytics, which strengthen both their contextual relevance and generalizability to similar industrial settings.

### 5.5 Challenges and Methodological Limitations

Despite the study's strengths, several limitations warrant discussion. Access to proprietary energy usage data was constrained in several facilities, limiting comparative benchmarking. Furthermore, while coconut fiber showed promising thermal performance, its lifecycle metrics remain understudied in standardized LCA frameworks, posing a barrier to broader policy acceptance. Structurally, retrofitting required downtime and infrastructural flexibility not available in all facilities, potentially constraining replication.

The interdisciplinary integration of architecture, environmental policy, and spatial data analysis also required methodological trade-offs in terms of depth versus breadth, which may limit the analytical resolution in specific sub-domains such as acoustics or embodied energy.

### 5.6 Economic Feasibility and Strategic Viability

Economic viability was a central concern in stakeholder interviews and field audits. While initial costs of retrofitting and bio-material procurement were moderately higher than conventional alternatives, return-on-investment analysis indicated full payback within two to three operational cycles. This was largely due to lowered utility bills, reduced material waste, and enhanced employee productivity linked to thermal and visual comfort.

Coconut by-products—abundant in Batam and the surrounding archipelago—offered low-cost, low-transport ecological alternatives. Their use created potential for regional circular economies involving material processing SMEs and green-label supply chains. Furthermore, spatial strategies such as airflow zoning and passive ventilation significantly reduced dependency on energy-intensive HVAC systems.

Furthermore, one of the most compelling economic innovations observed at PT Heng Guan was the valorization of coconut shells (tempurung) as a renewable fuel source for industrial heating systems. This strategy not only replaced fossil-based heating but also utilized an abundant by-product of the manufacturing process, contributing to both energy efficiency and cost savings.

***Figure 18.*** *Energy Efficiency through Coconut Shell Fuel Substitution*

This diagram illustrates the closed-loop energy model adopted at the facility, where coconut shells are repurposed as solid biomass fuel. It demonstrates how thermal systems were adapted to accommodate the combustion characteristics of coconut-based fuel, thereby reducing dependency on fossil inputs by approximately 28%, as reported in field observations and performance logs (Munir, 2020). Beyond environmental benefits, the substitution strategy also decreased procurement and waste management costs, underscoring the alignment between circular resource use and operational resilience.

### 5.7 Waste Reuse through 3R (Reduce, Reuse, Recycle)

3R in waste reuse is done by 1) reduce (reducing waste with a more efficient production design); 2) reuse (reusing materials that are still suitable for use in the production process or other needs), and 3) recycle (processing waste into new materials that are useful for production or resale). The 3R will provide benefits in reducing industrial waste, saving resources, and supporting the circular economy.


***Figure 19.*** *Waste Installation Arrangement of PT. Heng Guan Batam Source: processed based on field observations and measurements, 2025*

PT Heng Guan Batam is an example of how a company can transform into an environmentally friendly business. In this process, PT. Heng Guan Batam can do several things. One of them is improving the waste management process. PT. Heng Guan Batam can build a more efficient and environmentally friendly waste management system. Coconut waste produced from the processing process must be processed in a way that allows it to be recycled, reused, or turned into a by-product that has added value. The company then began to convert the waste they created into fertilizer. Currently, waste from the IPAL is processed into organic fertilizer. Previously, IPAL waste was put into sacks and dumped in the landfill.

Overall, the spatial-material framework demonstrated in this study offers a viable path to economic and ecological balance. It aligns with national green certification protocols (e.g., SNI ISO 14001), emerging ESG standards, and the incentives outlined in Indonesia's Industry 4.0 roadmap.

This discussion thus affirms that sustainable industrial transformation in tropical contexts is not only technically feasible but economically rational when approached through an integrated, spatial-material lens.

## 5. Conclusion

This study explored how the integration of coconut-based eco-materials and territorial spatial design can support sustainable industrial transformation in Batam, Indonesia. By combining qualitative fieldwork, spatial analysis, and conceptual synthesis, the research provided a comprehensive understanding of how architectural retrofitting and material innovation jointly contribute to environmental performance and operational efficiency in tropical manufacturing settings.

The findings confirmed that coconut-derived materials, when applied within spatially controlled industrial layouts, significantly enhance thermal comfort, reduce embodied carbon, and support material circularity. Facilities that implemented clear spatial zoning and adopted locally sourced natural materials demonstrated measurable improvements in energy and water efficiency, as well as enhanced employee engagement. These outcomes validated the central premise that spatial and material sustainability are mutually reinforcing.

From a theoretical standpoint, the study contributed to bridging disciplinary gaps between industrial ecology, architectural design, and circular economy frameworks. The adaptation of concepts such as "kontrol ruang" and "territorial hierarchy" in industrial contexts introduced a novel lens through which spatial organization can shape ecological behavior and resource governance. Practically, the research offers a replicable framework for other Southeast Asian industrial zones seeking to retrofit existing infrastructures using affordable, locally available nature-based materials.

The study recommends that architects, facility managers, and policymakers adopt a hybrid approach to industrial retrofitting—one that leverages spatial logic and material sustainability in tandem. Regulatory institutions may consider integrating spatial performance indicators into environmental certification standards, while industries should invest in modular systems that facilitate behavioral control and green material adoption.

Future research may focus on conducting **quantitative lifecycle assessments (LCA)** of coconut-based construction elements to establish standardized environmental performance metrics. Additionally, comparative studies across industrial typologies and climatic zones could validate the generalizability of the proposed model. Longitudinal research is also encouraged to observe how spatial-material transformations evolve over time, particularly in post-retrofit operational stages.

In conclusion, the integration of territorial spatial planning and coconut-based eco-materials offers a promising and context-sensitive strategy for green industrial transformation. Rather than treating sustainability as a technical add-on, this study positions it as an embedded, behavioral, and spatially constructed process—one that is both locally grounded and globally relevant.

## Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Author contributions:** Hendro Murtiono: Conceptualization, Methodology, Field Investigation, Writing – Original Draft. Atik Suprapti: Supervision, Methodological Guidance, Review and Editing. Suzanna Ratih Sari: Data Analysis, Resources, Visualization. Resha Rizkiyanto: Spatial Mapping, Stakeholder Engagement, Validation. All authors have read and approved the final version of the manuscript

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