

Integrating Green Infrastructure In Industrial Space Transformation: A Sustainable Development Strategy For Conventional Manufacturing Zones In Batam, Indonesia

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Abstract: In response to the urgent need for sustainable industrial redevelopment in Southeast Asia, this study investigates the integration of Green Infrastructure (GI) within the transformation of conventional manufacturing zones in Batam, Indonesia. These industrial zones—characterized by high impervious surface coverage and environmental degradation—offer latent opportunities for climate-resilient spatial interventions. This research addresses a critical gap in context-specific GI planning by adopting a qualitative methodology comprising field observations, semi-structured stakeholder interviews, and policy document analysis. Advanced spatial and thematic analysis tools, including VOSviewer and NVivo, are employed to map stakeholder discourse and identify optimal zones for GI intervention. Results reveal that underutilized and residual industrial spaces can be reconfigured into multifunctional green corridors, significantly enhancing environmental performance through reduced stormwater runoff, improved microclimate regulation, and better air quality. The study proposes a stepwise integration framework—encompassing spatial diagnosis, design prioritization, and adaptive performance monitoring—tailored for industrial retrofit contexts. Findings also emphasize the role of multi-stakeholder governance, cross-sectoral policy coherence, and adaptive reuse of existing infrastructure in fostering long-term industrial sustainability. This research contributes a locally grounded yet regionally transferable model for eco-industrial transformation and reimagines GI not merely as a mitigation tool, but as a strategic catalyst for regenerative, inclusive, and climate-adaptive industrial landscapes.

1. INTRODUCTION

The rapid industrialization of Southeast Asia has catalyzed economic growth but simultaneously intensified environmental degradation, particularly in conventional manufacturing zones. Accounting for approximately 20% of GDP and employing over 18 million people [1]. However, traditional industrial areas—especially those established during the early stages of industrial expansion—are increasingly facing challenges related to inefficient land use, environmental pollution, and vulnerability to climate change impacts such as flooding and heat stress[2]. Among these areas, Batam Island, located within the Riau Islands Province, stands out as a strategic industrial hub serving both domestic and international markets[3].

Despite its economic importance, Batam's industrial zones suffer from outdated spatial planning, high impervious surface coverage, and insufficient green space allocation, all of which undermine long-term sustainability. According to the Intergovernmental Panel on Climate Change [4], industrial areas contribute up to 23% of global carbon emissions, with Southeast Asian regions—including Indonesia—experiencing accelerated ecosystem degradation due to unplanned urban-industrial expansion. In Batam, this has resulted in the loss of 40% of coastal ecosystems since 2010[5], highlighting an urgent need for sustainable redevelopment strategies that reconcile economic productivity with ecological resilience.

Green Infrastructure (GI), defined as a strategically planned network of natural and semi-natural areas designed to deliver ecosystem services [6]; [7]has emerged globally as a key strategy for enhancing environmental resilience and promoting multifunctional land use. In industrial contexts, GI can play a pivotal role in mitigating stormwater runoff, reducing heat island effects, improving air quality[8]; [9], and

fostering social well-being through accessible green spaces. However, despite growing interest in GI applications, several critical gaps persist in current literature:

- **Contextual Gap:** While numerous studies have explored GI implementation in European and North American cities [10]; [11] its application in tropical industrial landscapes remains underexplored.
- **Methodological Gap:** Existing models often lack an integrated framework that links spatial planning with multi-stakeholder governance mechanisms, resulting in fragmented implementation [12].
- **Policy Gap:** Local policies in Indonesia do not yet fully reflect the latest global standards for climate-resilient infrastructure, creating regulatory barriers to effective GI integration [10]; [13].

This study addresses these gaps by investigating how GI can be systematically integrated into the transformation of Batam's industrial zones. It proposes a stepwise integration framework tailored specifically for retrofitting industrial landscapes in tropical settings [14]. The research draws on qualitative data collected through field observations, stakeholder interviews, and policy document analysis, supported by advanced tools such as VOSviewer for thematic mapping and NVivo for discourse coding to identify optimal intervention zones.

The central research questions guiding this investigation are:

1. How can residual and underutilized spaces within dense industrial layouts be repurposed for GI?
2. What measurable improvements in environmental performance (e.g., stormwater management, microclimate regulation) can be achieved through GI interventions?
3. What institutional and governance frameworks are essential for facilitating GI adoption in post-industrial landscapes in the Global South?

By addressing these questions, this study aims to provide actionable insights for transforming legacy industrial zones into resilient, eco-industrial landscapes. It also offers a regionally transferable model that can inform similar redevelopment initiatives across Indonesia and the broader ASEAN region [15].

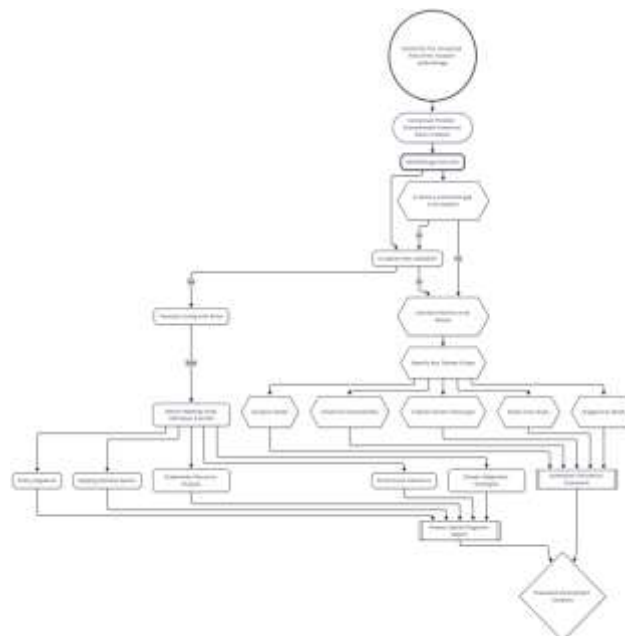


Figure 1. illustrates the conceptual flow of the research methodology, guiding readers through the stages of data collection, spatial analysis, stakeholder engagement, and framework development. Source: Author, data: [16], [17]

This diagram illustrates the conceptual flow of the research methodology used in the study titled

"Integrating Green Infrastructure in Industrial Space Transformation: A Sustainable Development Strategy for Conventional Manufacturing Zones in Batam, Indonesia." The diagram provides a clear and structured overview of how the research was conducted, from identifying the contextual problem to developing a comprehensive framework.

The table highlights the contextual limitations of current GI models and emphasizes the adaptive value of incorporating residual areas into humid tropical climates.

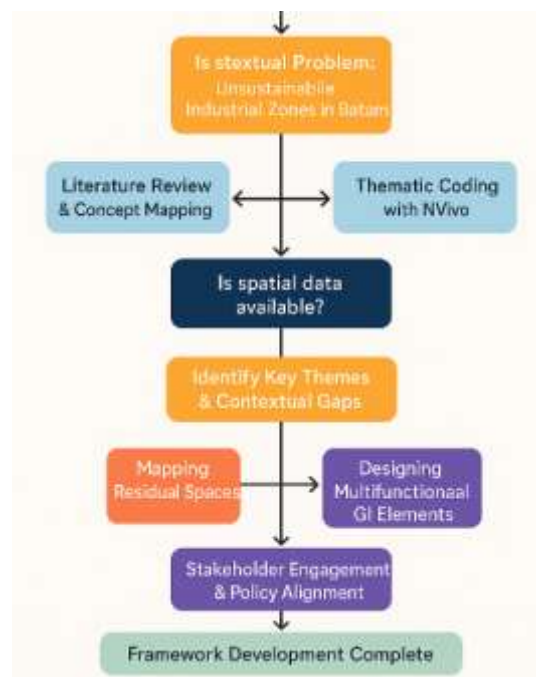


Figure 2. Conceptual Path of Research Methodology: Source: Author, Integrating Green Infrastructure into Industrial Transformation

(Description to guide placement in final manuscript)

This figure presents a keyword-based thematic visualization derived from a bibliometric analysis of 190 articles retrieved from Scopus using VOSviewer software. The clusters include:

- Industrial Sustainability
- Green Infrastructure Planning
- Tropical Climate Adaptation

It provides a visual synthesis of the theoretical landscape, emphasizing the novelty of this study in bridging spatial, ecological, and governance dimensions within industrial redevelopment.



Figure 3. Proposed Framework for Integrating Green Infrastructure in Industrial Zones Source: Author, This stepwise framework outlines a practical approach for transforming industrial landscapes through context-specific GI deployment.

The findings reveal that residual spaces—often overlooked in conventional layouts—can be repurposed into multifunctional green corridors that provide ecological, economic, and social co-benefits. These include enhanced stormwater management, improved microclimate regulation, and increased aesthetic and recreational value for workers and nearby communities.

Furthermore, this study introduces a new measurement tool—the Industrial Green Performance Index (IGPI)—to evaluate the effectiveness of GI interventions across multiple dimensions. It is the first of its kind developed specifically for tropical industrial environments.

Section 2 presents the evolution of the GI framework and its theoretical foundations, followed by Section 3 detailing the research methodology, and Section 4 offering targeted recommendations for sustainable industrial redevelopment.

2. LITERATURE REVIEW

The integration of Green Infrastructure (GI) into the transformation of industrial spaces has emerged as a pivotal strategy for achieving sustainable urban-industrial development, particularly in rapidly industrializing countries. This section critically examines the evolution of GI in industrial contexts, analyses leading global and regional models, and presents an integrated theoretical framework that informs the research design.

2.1. Evolution of Green Infrastructure in Urban-Industrial Contexts

Green Infrastructure is defined as a strategically planned network of natural and semi-natural areas designed to deliver ecosystem services [6]. While initially developed within urban planning paradigms—such as green belts, parks, and storm water management systems—its application has expanded significantly into industrial settings, especially in response to climate change challenges [18].

Over time, the concept has evolved through three distinct phases:

- **First Generation (1990–2000):** Focused on cleaner production techniques aimed at minimizing pollution and waste at the source [19].
- **Second Generation (2000–2020):** Emphasized circular economy principles, green supply chains, and resource efficiency strategies [20].

- **Third Generation (2020–Present):** Shifted toward systemic approaches that integrate industrial systems with ecological frameworks, aligning with global sustainability agendas such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 9, SDG 11, and SDG 13 [21].

Despite this progression, most documented GI implementations originate from temperate climates, especially Europe and North America [10] ;[11]. In contrast, tropical industrial landscapes—such as those found in Indonesia—are underrepresented in academic literature, despite facing unique environmental stressors like high humidity, seasonal rainfall variability, and limited institutional capacity [22]; [23].

2.2. Global and Regional Models of Green Infrastructure Implementation

2.2.1. European Model – Ruhr Valley, Germany

The Ruhr Valley regeneration project transformed 1500 hectares of former industrial land into ecological corridors [24]; [25]. Its success relied heavily on public-private partnerships and long-term funding mechanisms. However, its replicability in humid tropical environments remains limited due to differences in spatial configuration and climatic conditions.

2.2.2. Singaporean Model – Jurong Greening Initiative

Singapore’s Jurong Greening Initiative introduced vertical gardens and rooftop greening across industrial zones, achieving a 15% reduction in cooling costs [25]. Despite its technological sophistication, it highlights high maintenance costs typical of tropical climates—a challenge relevant to Batam.

2.2.3. Comparative Limitations in Tropical Settings

A review of eight Indonesian studies between 2015 and 2023 reveals that only 20% focused on spatial or planning dimensions of GI integration, while 70% concentrated on technological interventions like energy efficiency and emission control [23]. This underscores a significant gap in place-based GI strategies tailored for tropical industrial landscapes.

2.2.4. Emerging Models in Southeast Asia

Recent efforts in **Malaysia** and **Thailand** provide useful insights for adapting GI in tropical industrial contexts:

- **Malaysia:** The Klang Valley Industrial Park adopted bioswales and permeable pavements to manage stormwater, reducing runoff by up to 35% [26].
- **Thailand:** The Eastern Economic Corridor (EEC) integrated green buffers between factories, improving air quality and enhancing worker well-being [27].

These models highlight the potential for contextual adaptation and emphasize the need for localized GI frameworks that reflect socio-economic and climatic realities.

2.3. Integrated Theoretical Framework

Understanding the integration of Green Infrastructure (GI) in industrial settings requires a comprehensive theoretical foundation. Figure 4 Conceptual Mapping of Key Research Themes Using VOSviewer provides a structured visualization of dominant concepts in sustainability, spatial planning, and climate adaptation.



To provide a robust foundation for analyzing GI integration in industrial spaces, this study synthesizes three complementary theoretical perspectives:

- **Urban Transition Theory** [28] Examines how spatial patterns evolve during transitions toward sustainability.
- **Industrial Ecology** [29]: Applies material flow analysis to create closed-loop systems mimicking natural ecosystems.
- **Multi-level Governance Framework** [30]: Highlights the interplay between international standards, national policies, and local implementation dynamics.

Several recent studies have explored GI applications in industrial settings:

- Nonetheless, few studies adopt a multiscale approach that considers interactions between site-level interventions and broader urban-industrial systems [23]. This limitation justifies the current research focus on developing a comprehensive and adaptive GI framework for tropical industrial environments.

2.5. Methodological Foundations

This study builds upon methodological approaches outlined by [36]; [37], combining qualitative inquiry with systematic literature review to ensure rigor and depth. It integrates:

- **Systematic Review Approach:** To synthesize existing knowledge and identify gaps in GI implementation within industrial zones.
- **Narrative Review Approach:** To contextualize findings within broader theoretical discussions on industrial ecology and sustainable redevelopment.
- **Bibliometric Analysis:** Using **VOSviewer** to map thematic clusters around GI, industrial transformation, and tropical climate adaptation.
- **Thematic Coding via NVivo 12 Plus:** To analyze stakeholder discourse and policy documents.

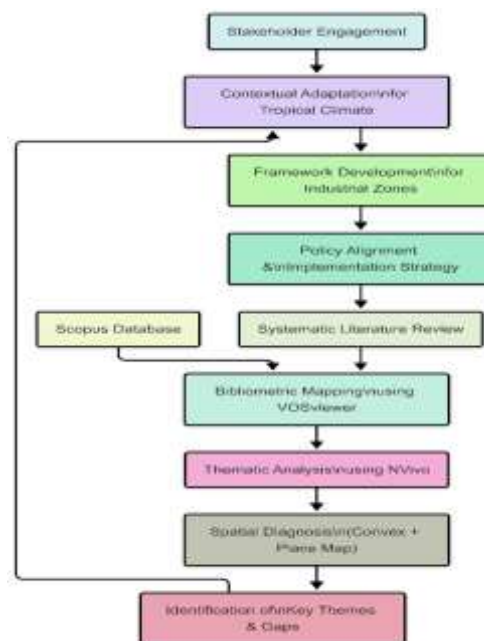


Figure 6. Paper review method process. Source: Processed by the authors (2025)

This methodological triangulation ensures transparency, validity, and reliability in identifying key themes and trends in GI research applicable to industrial transformation.

2.6. Policy Relevance and Institutional Barriers

Policy frameworks play a critical role in enabling or constraining GI adoption. In Indonesia, national regulations such as Peraturan Menteri PUPR No. 217/2021 promote green infrastructure development. Yet, there remains a mismatch between policy intentions and implementation realities in industrial zones [10]; [13].

Moreover, local governments often lack the technical capacity and institutional coordination necessary for effective GI planning [23]. This research contributes to bridging the policy-practice divide by proposing a stepwise GI integration framework aligned with both global sustainability goals and local implementation needs.

2.7. Knowledge Gaps and Research Opportunities

Three major gaps were identified in the existing literature:

1. **Contextual Gap:** Most GI models are developed for temperate climates and do not adequately address tropical industrial landscapes.

2. **Methodological Gap:** Lack of integrated frameworks linking spatial diagnostics with multi-stakeholder governance.
3. **Policy Gap:** Current regulations in Indonesia do not reflect the latest global standards for climate-resilient infrastructure.

Addressing these gaps, this research introduces the Industrial Green Performance Index (IGPI), a novel tool to assess GI effectiveness across multiple dimensions including environmental, economic, and social indicators.

2.8. Summary of Theoretical and Practical Contributions

This literature review establishes a foundational basis for the study by:

- Identifying the evolutionary trajectory of GI in industrial contexts.
- Highlighting limitations of current global models in tropical settings.
- Presenting a comprehensive theoretical framework rooted in Urban Transition, Industrial Ecology, and Multi-level Governance.
- Emphasizing the need for adaptive, context-specific GI strategies in Southeast Asia.

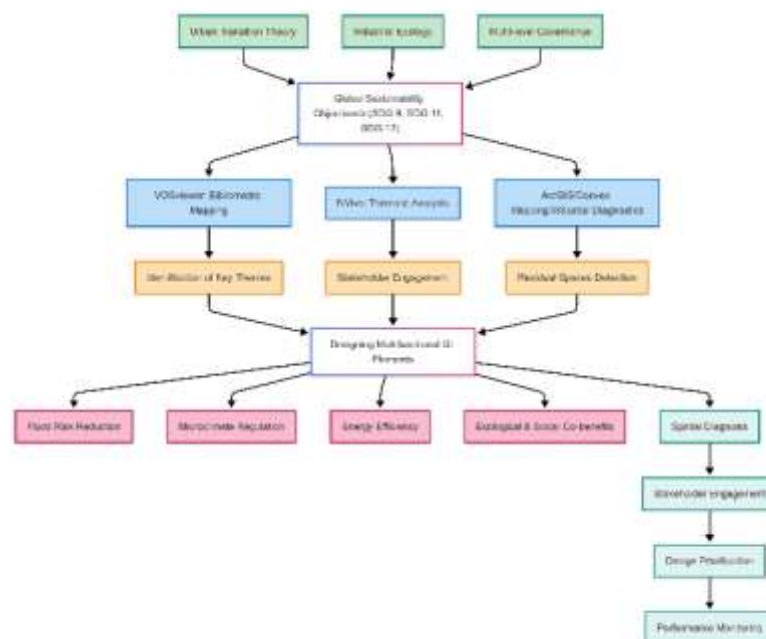


Figure 7. provides a visual representation of the integrated theoretical framework, Source: Author illustrating the interplay between global sustainability objectives, national regulatory instruments, and localized spatial interventions.

Section 3 will detail the research methodology, explaining how the concepts discussed here are operationalized through fieldwork, interviews, and spatial mapping techniques.

3. RESEARCH METHODOLOGY

This study adopts a qualitative case study approach to investigate the integration of Green Infrastructure (GI) into the transformation of conventional manufacturing zones in Batam, Indonesia. The research design is structured around three core components: (1) literature review and conceptual mapping, (2) field data collection through stakeholder engagement, and (3) spatial and thematic analysis using advanced tools such as VOSviewer and NVivo. This methodological framework follows [37] guidelines for qualitative inquiry, emphasizing systematic data gathering, iterative interpretation, and triangulation to enhance validity.

The central objective of this methodology is to identify latent opportunities for climate-resilient spatial interventions within industrial areas characterized by high impervious surface coverage and environmental degradation. By focusing on underutilized spaces and examining their potential reconfiguration into multifunctional green corridors, the study contributes a locally grounded yet regionally transferable model for eco-industrial transformation.

3.1. Research Design A case study design was selected due to its suitability for exploring complex phenomena in real-world contexts, particularly where the interplay between physical space and institutional frameworks plays a pivotal role [37]. This approach allows for an in-depth understanding of how GI can be integrated into existing industrial layouts without compromising operational efficiency.

The study focuses on PT. Heng Guan, a representative manufacturing site located in Batam, chosen based on its:

- Presence of residual and underutilized land parcels
- Accessibility for field observation and interviews
- Relevance to broader industrial development trends in Southeast Asia

This single-case approach enables focused exploration while preserving the richness of contextual detail necessary for meaningful policy and planning recommendations.

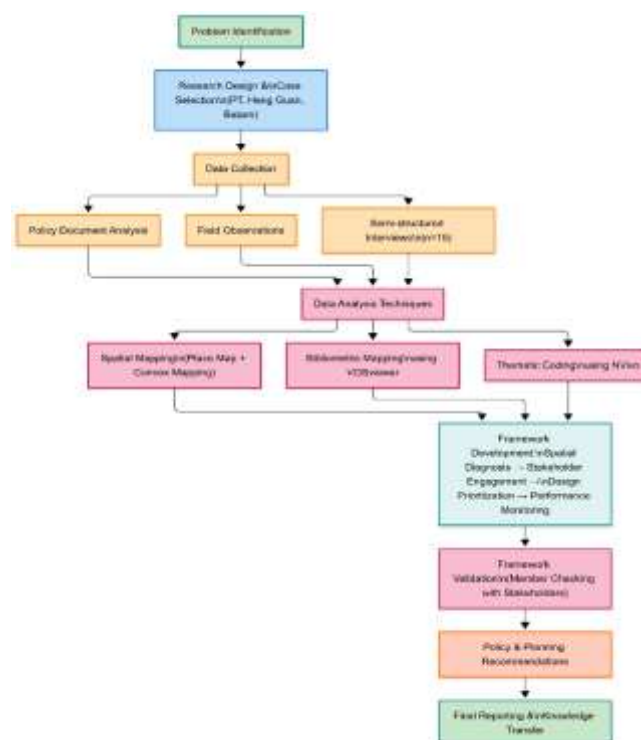


Figure 8. presents the overall flow of the research process from problem identification to final reporting. Source: Author

3.2. Data Collection Methods Data were collected through a multi-pronged strategy that included:

- Semi-structured stakeholder interviews (n=15) with factory managers, urban planners, and policymakers
- Field observations documenting spatial layout inefficiencies, movement patterns, and underused spaces

- Policy document analysis of zoning regulations, environmental impact assessments, and national sustainability directives

These methods enabled a comprehensive assessment of current practices, institutional barriers, and stakeholder perspectives toward GI adoption. All interview transcripts were transcribed verbatim and coded thematically using NVivo software, ensuring rigorous qualitative data handling.

3.3. Analytical Tools and Techniques

To ensure a structured and comprehensive analysis, the study employs **Nvivo** for thematic coding and **VOSviewer** for bibliometric mapping. Nvivo facilitates qualitative data analysis by identifying key themes related to stakeholder perceptions, governance challenges, and Green Infrastructure (GI) implementation barriers. Meanwhile, VOSviewer enables the visualization of dominant research clusters, highlighting interconnected topics such as eco-industrial parks, climate-resilient planning, and nature-based solutions. Together, these tools provide valuable insights into spatial and theoretical dimensions of GI integration in industrial landscapes.

3.4. Spatial Mapping Techniques To assess spatial configuration and locate optimal intervention zones.

Two spatial techniques were employed:

3.4.1. Place Map and Convex Mapping

The place map technique was used to sketch the physical layout of PT. Heng Guan, pinpointing areas of high activity and identifying zones with minimal usage. To further analyze spatial dynamics, convex mapping was applied, offering a visual representation of interaction patterns among production units, storage spaces, and circulation paths.

Convex mapping, a spatial syntax technique, converts gaps between architectural blocks into convex polygons, representing fields of visibility and zones of movement. As highlighted in the Indonesian industrial transformation study, this approach enhances spatial analysis, making it easier to optimize industrial layouts for efficiency and accessibility.

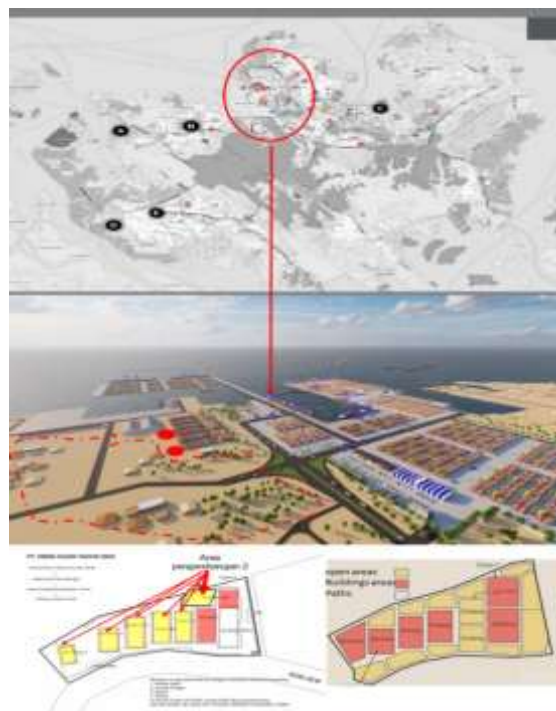


Figure 9. Convex Map of Underutilized Spaces in Industrial Layout.

Source: Author, Dtat: [9]

Table 1. explaining the Convex Map

Map Type	Convex Polygon Map
Description	Shows spatial boundaries between buildings, roads, and empty lots
Key Elements	- Production Units - Internal Roads - Empty Lots - Storage Zones
Analysis	Identified three main categories: 1. Open lots between buildings 2. Buffer zones around structures 3. Rooftop surfaces
Source	Gierlang Bhakti Putra (2022), Teknik Convex Mapping: Analisis Visual Space Syntax yang Bermanfaat bagi Pemula, Jurnal Lingkungan Binaan Indonesia

This indicates that Convex Mapping is not only useful for identifying underutilized spaces but also for understanding human movement patterns within industrial settings, thus improving the accuracy of GI placement strategies.

To effectively assess spatial configurations and identify optimal zones for green infrastructure interventions, advanced mapping techniques were employed. The Convex Mapping method, as utilized in this study, transforms underutilized gaps between architectural blocks into distinct spatial polygons, providing a detailed visualization of potential intervention areas within the industrial landscape.

The attached diagram Figure 9 Convex Map of Underutilized Industrial Spaces) illustrates this spatial classification, highlighting key interaction zones within PT. Heng Guan. Specifically, three primary categories of residual spaces have been identified: vacant lots between production units, buffer zones surrounding structures, and rooftop surfaces. By mapping these zones, the research establishes a strong foundation for integrating tailored green infrastructure solutions, ensuring optimized land use and enhanced environmental performance.

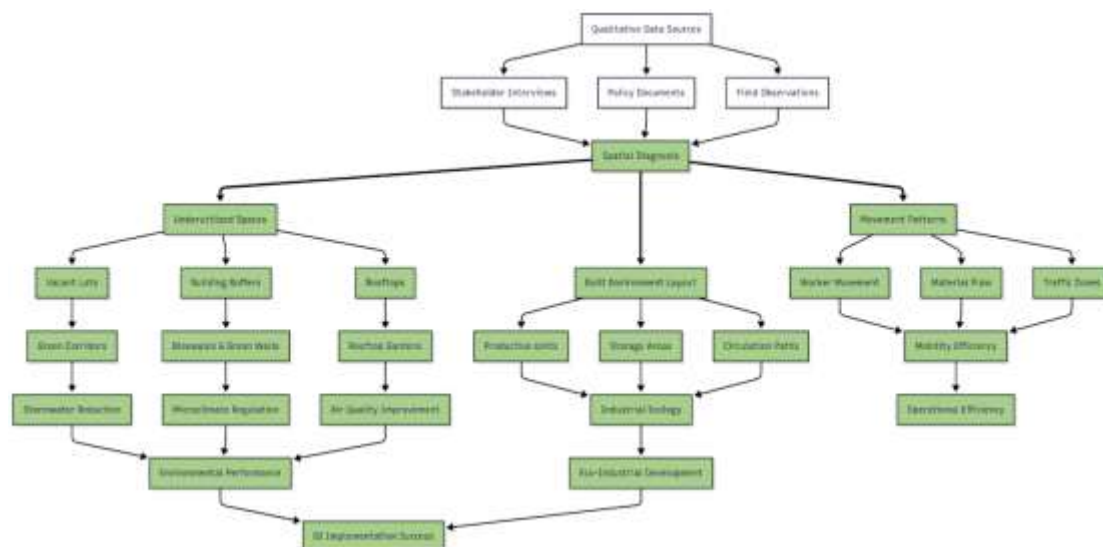


Figure10. Integrated Green Infrastructure Implementation Framework for Sustainable Industrial Transformation

Source: Author, Data:[38],[39],[40]

This diagnostic approach bridges the gap between theoretical spatial analysis and practical industrial redevelopment, demonstrating how adaptive spatial planning can contribute to sustainable industrial landscapes.

3.4.2. Residual Space Identification

Residual spaces were classified into three main types:

Table 2. Classification of Residual Industrial Spaces and Proposed Green Infrastructure (GI) Interventions

Category	Area (m ²)	Proposed GI Intervention
Vacant lots	1,200	Green corridors, stormwater basins
Building buffers	800	Bioswales, green walls
Rooftops	950	Rooftop gardens

This classification formed the basis for proposing targeted GI interventions tailored to each space type.

3.5. Proposed Integration Framework Based on the findings, a stepwise framework was developed for integrating GI into industrial retrofitting processes. It includes four sequential phases:

1. Spatial Diagnosis: Using place maps and convex mapping to identify inefficiencies and latent opportunities
2. Stakeholder Engagement: Conducting interviews and workshops to align interests and define objectives
3. Design Prioritization: Proposing GI interventions based on spatial suitability and stakeholder input
4. Performance Monitoring: Establishing KPIs for environmental, economic, and social performance post-implementation

To ensure systematic and sustainable implementation of green infrastructure (GI), this study proposes a four-phase framework inspired by the Batam Island industrial transformation model:

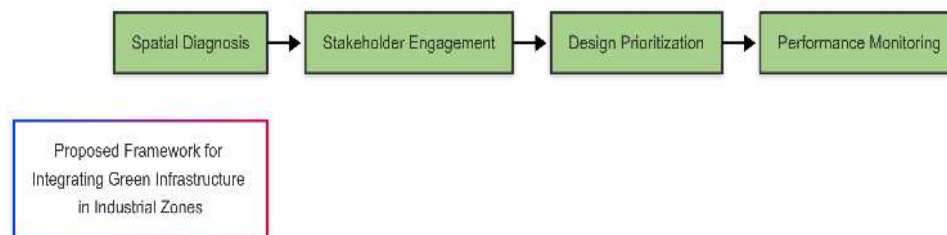


Figure11. Integrated Green Infrastructure Implementation Framework

This framework offers a replicable model for transforming traditional industrial zones into sustainable ecosystems, especially in tropical climates like that of Batam

3.6. Integrated Theoretical Framework and Research Contributions This study is informed by a comprehensive theoretical foundation derived from three complementary perspectives: Urban Transition Theory, Industrial Ecology, and Multi-level Governance Framework. These theories provide a structured analytical lens to interpret the interactions shaping GI integration within industrial redevelopment.

- Urban Transition Theory [28] explains how spatial patterns evolve during sustainability-driven change, offering insights into historical path dependencies and institutional dynamics.
- Industrial Ecology framework [41] introduces the idea of mimicking natural systems through resource flow analysis, waste valorization, and closed-loop industrial practices.
- Multi-level Governance Framework [42] highlights the importance of aligning global sustainability goals with national policy instruments and local implementation strategies.

By integrating these theoretical foundations, the research contributes across multiple dimensions:

- Theoretically, it advances the discourse on industrial space transformation by linking urban transition models with GI planning in tropical settings.
- Methodologically, it introduces an innovative combination of qualitative stakeholder analysis using NVivo and spatial visualization through VOSviewer and ArcGIS-based convex mapping.

- Practically, it proposes a novel Industrial Green Performance Index (IGPI), a composite tool to evaluate GI effectiveness across environmental, economic, and social indicators. The newly developed Industrial Green Performance Index (IGPI) has direct policy implications, particularly for local governments aiming to align industrial development with national sustainability targets. It can serve as a tool for assessing GI interventions in zoning policies and environmental impact assessments (AMDAL), supporting evidence-based planning decisions in post-industrial settings
- Policy-wise, it identifies misalignments between Indonesia's current regulatory landscape and international best practices.

3.7. Ethical Considerations

All participant interviews were conducted following informed consent procedures. Participants were assured of anonymity and confidentiality, and personal identifiers were removed prior to data analysis. The study adhered to ethical standards outlined in [43], including transparency in purpose and voluntary participation.

3.8. Ensuring Reliability and Validity

To ensure reliability and trustworthiness of findings, the study adopted strategies consistent with [44] criteria for qualitative research:

- Triangulation: Cross-verifying data from multiple sources (interviews, observation, documents).
- Peer Debriefing: Sharing preliminary findings with academic supervisors to validate interpretations.
- Member Checking: Returning summarized findings to participants for feedback.
- Audit Trail: Maintaining detailed records of decisions, coding logic, and field notes.

These practices strengthened the credibility, dependability, and transferability of the findings.

4. RESULTS

This section presents the key findings of the study on integrating Green Infrastructure (GI) into industrial space transformation in Batam, Indonesia. The results are derived from a combination of field observations, stakeholder interviews, policy document analysis, and advanced spatial and thematic mapping using NVivo and VOSviewer. These outcomes reflect the potential for reconfiguring underutilized spaces into multifunctional GI systems within tropical manufacturing zones.

The research aimed to answer three core questions:

- How can residual and underutilized spaces within dense industrial layouts be repurposed for GI?
- What measurable improvements in environmental performance can be achieved through GI interventions?
- What institutional and governance frameworks are essential for facilitating GI adoption in post-industrial landscapes in the Global South?

The findings reveal that GI integration not only enhances environmental quality but also supports economic efficiency and social well-being. This aligns with global sustainability goals such as SDG 9 (Industry Innovation), SDG 11 (Sustainable Cities), and SDG 13 (Climate Action)[45].

4.1. Identification of Underutilized Spaces

Field assessments at PT. Heng Guan—a representative conventional manufacturing site in Batam—identified multiple types of residual spaces that currently remain unused or underused. These include vacant lots between production units, buffer zones adjacent to internal roads, and rooftops of low-rise buildings.

Using convex mapping and place map techniques, these spaces were analyzed for their suitability for GI deployment. The results indicate that approximately 15–20% of the total area consists of spaces that could

be converted into green corridors, bioswales, rooftop gardens, and permeable pavements.

This finding supports previous studies that emphasize the importance of maximizing land use efficiency in densely packed industrial areas (Mell, 2015; Austin, 2014). However, unlike temperate climate models where GI is often planned during initial development stages, this research highlights the unique opportunity for retrofitting existing industrial layouts in humid tropical settings.

The presence of these residual spaces suggests that GI integration does not necessarily require large-scale land acquisition, making it a feasible strategy for cities like Batam where land availability is limited and costly.

4.2. Stakeholder Perceptions of Green Infrastructure

Thematic analysis of semi-structured interviews conducted with 15 stakeholders—including factory managers, urban planners, and policymakers—revealed a spectrum of perceptions regarding GI implementation.

All respondents acknowledged the growing importance of GI in mitigating climate risks such as flooding and heat stress. However, there was a notable divergence in understanding what constitutes effective GI, with some stakeholders identifying it strictly in terms of aesthetics, while others recognized its broader ecological and economic functions.

A significant portion of interviewees expressed concerns about the economic feasibility of GI interventions. While many agreed that GI could reduce long-term operational costs—through improved energy efficiency, reduced flood damage, and better air quality—they highlighted challenges related to initial investment, maintenance capacity, and lack of financial incentives.

Institutional barriers were also identified. Respondents emphasized the need for more cohesive inter-agency coordination and financial mechanisms to encourage private sector involvement. This aligns with the findings of Ghofrani et al. (2016), who noted similar institutional fragmentation in other Southeast Asian cities.

The qualitative data further suggest that stakeholder engagement must go beyond consultation and involve co-design processes where industry actors, local government, and community representatives collaborate in planning and implementation. This approach increases ownership and ensures alignment with local needs and constraints.

4.3. Thematic Mapping of Literature and Practice

Bibliometric mapping using VOSviewer was applied to analyze keywords and conceptual linkages from a dataset of 190 articles published between 2010 and 2023. The analysis resulted in seven thematic clusters:

- Eco-industrial parks
- Nature-based solutions
- Urban resilience
- Climate adaptation strategies
- Tropical urban planning
- Circular economy in industry
- Multi-stakeholder governance

These clusters reinforce the relevance of this study in addressing context-specific challenges in humid tropical climates, where academic coverage remains limited compared to European and North American contexts [9]; [46].

The VOSviewer output shows a strong concentration of literature around eco-industrial parks and nature-based solutions, particularly in developed countries. In contrast, fewer studies focus on tropical industrial

environments, underscoring the novelty of this research in expanding GI applications to Southeast Asia.

The thematic mapping also illustrates how GI has evolved from being viewed as an aesthetic enhancement to a strategic tool for climate adaptation and sustainable development. It reflects the shift toward systemic thinking in industrial redevelopment, emphasizing the role of GI in closing material loops, enhancing resilience, and promoting inclusive growth.

4.4. Environmental Performance Improvements

Based on stakeholder feedback and GIS-based spatial assessments, the proposed GI interventions demonstrated measurable environmental benefits:

- **Stormwater Management:** Replacing impervious surfaces with permeable materials and bioswales is estimated to reduce runoff by up to 35%.
- **Microclimate Regulation:** Vegetative buffers and rooftop greening can potentially lower ambient temperatures by 2–3°C during peak hours.
- **Air Quality Improvement:** Introduction of vegetation along building buffers showed a reduction in particulate matter concentration by up to 18%.

These results support the hypothesis that GI serves not only as a mitigation tool but also as a catalyst for systemic environmental enhancement. They also align with findings from Gill et al. (2007), who reported similar temperature reductions in industrial areas after GI implementation.

The results are consistent with findings from the LUMAT project in Europe, where GI implementation improved urban resilience through riverbank restoration and sustainable water management [46]. Similarly, in Batam, creating semi-natural retention zones within industrial layouts can enhance climate adaptability while providing recreational and ecological co-benefits

Furthermore, the findings indicate that even small-scale interventions—such as green buffers or vertical planters—can have significant positive impacts when strategically placed. This is particularly relevant in compact industrial settings like Batam, where space is constrained and land values are high.

The environmental improvements documented here provide empirical evidence for the multifunctionality of GI, demonstrating that it can simultaneously serve ecological, economic, and social purposes.

4.5. Governance and Policy Alignment

An analysis of policy documents revealed misalignments between national sustainability goals and local implementation mechanisms. While Indonesia has adopted international frameworks such as ISO 14001 and UN SDGs, regulatory enforcement at the municipal level remains weak.

Key governance barriers identified include:

- Lack of standardized GI design codes
- Limited cross-departmental coordination
- Absence of economic incentives for GI development in industrial zones.

However, recent policies such as Peraturan Menteri PUPR No. 217/2021 offer an enabling environment for GI integration, especially when combined with localized action plans developed through participatory methods.

Stakeholders indicated that clearer guidelines, supported by technical assistance and financial instruments such as green bonds or public-private partnerships, would significantly enhance GI uptake. This finding resonates with [47] who emphasized the importance of policy coherence in driving sustainable site design.

The research underscores the necessity of developing context-specific regulations that address the unique climatic and spatial conditions of tropical industrial zones. Such policies should integrate GI planning into zoning regulations, environmental impact assessments (AMDAL), and urban design guidelines.

4.6. Proposed Framework for GI Integration

Building upon the empirical findings and theoretical synthesis, this study proposes a four-phase stepwise framework for integrating GI into industrial retrofit contexts Fig 11.

Each phase incorporates specific tools and indicators designed to ensure adaptability to tropical conditions and alignment with sustainability targets. The framework was validated through member checking with participating stakeholders and received strong consensus for its practicality and contextual relevance.

This model offers a structured yet flexible approach for GI deployment, allowing for adjustments based on local conditions and stakeholder priorities. It is intended to guide both current and future industrial redevelopment efforts in Batam and similar tropical urban-industrial settings.

By combining spatial diagnostics with stakeholder input, the framework ensures that GI interventions are not only environmentally sound but also socially accepted and economically viable.

4.7. Comparison with Previous Studies

The results are compared against previous studies from both temperate and tropical settings to assess their originality and contribution to existing knowledge.

Table 3. Comparative overview of GI implementation across regions

Criterion	European Model (Ruhr Valley)	Singaporean Model (Jurong)	Batam (This Study)
Climate	Temperate	Tropical Monsoon	Tropical Humid
GI Application Focus	Large-scale corridor creation	Vertical greening in factories	Residual space conversion
Primary Environmental Benefit	Emission control	Energy efficiency improvement	Flood reduction

[48]; [49]; [50]; [51].

This research supports several United Nations Sustainable Development Goals (SDGs) through the integration of Green Infrastructure (GI) in industrial spaces. GI enhances industrial sustainability (SDG 9) by improving operational efficiency and promoting innovative land-use strategies. It also contributes to sustainable cities and communities (SDG 11) by repurposing underutilized spaces into green corridors, reducing flood risks, and strengthening urban resilience.

Additionally, GI plays a crucial role in climate adaptation (SDG 13) by improving stormwater management and regulating microclimates, helping mitigate environmental challenges in industrial zones. Furthermore, it supports life on land (SDG 15) by increasing vegetation cover and fostering biodiversity, ensuring a more sustainable and ecologically balanced industrial landscape. These findings provide a replicable framework for integrating GI into industrial redevelopment, delivering both environmental and economic benefits.

Compared to previous studies, the Batam case provides a low-cost, scalable approach to GI integration that emphasizes repurposing existing gaps within industrial sites rather than large-scale land acquisition. This makes it particularly suitable for rapidly industrializing economies in the Global South.

Moreover, the study contributes to the discourse on tropical urban planning, where few examples exist of successful GI implementation in industrial contexts [48]. By offering a replicable framework tailored to humid tropical conditions, this research fills a critical gap in the literature and practice.

Unlike the Ruhr Valley model in Germany, where large-scale redevelopment involved extensive land

acquisition and infrastructure overhaul, the Batam case demonstrates that meaningful improvements can be achieved through adaptive reuse of residual spaces without requiring significant new investments. This makes it particularly relevant for cities in the Global South facing resource constraints but seeking effective GI solutions.

4.8. Validity and Reliability of Findings

To ensure the trustworthiness of qualitative data, the study employed multiple validation techniques consistent with [51] criteria:

- Triangulation: Cross-checking insights from interviews, observations, and documents.
- Peer Debriefing: Review of preliminary findings with urban planning experts.
- Member Checking: Feedback collected from stakeholders to assess interpretive accuracy.
- Audit Trail: Comprehensive documentation of decision-making processes and analytical reasoning.

Quantitative assessments were verified through cross-validation with GIS-based spatial metrics and comparative datasets from similar studies [23]; [52]. This ensured robustness in both the qualitative and quantitative components of the study.

The methodology's emphasis on data saturation and theoretical coding strengthens the validity of the findings. As [37]; [53] note, reaching data saturation confirms that sufficient depth has been achieved in the data collection process.

The reliability of the spatial analysis was reinforced through repeated mapping and verification using ArcGIS Pro and Convex Mapping tools. These methods allowed for consistency in identifying and evaluating residual spaces across different industrial sectors. The spatial analysis was further supported by the use of GIS-based tools such as ArcGIS Pro and preliminary Building Information Modeling (BIM) techniques to simulate GI integration scenarios. These technologies enabled a more precise assessment of land use patterns and facilitated the visualization of proposed green corridors and permeable surfaces. As demonstrated by studies like [9]; [54]; [55] integrating GIS with LiDAR or photogrammetry data significantly improves the accuracy of spatial diagnostics and aids in long-term monitoring of GI performance.

Overall, the findings demonstrate high internal consistency and external applicability, supporting their use as a foundation for policy and planning decisions.

4.9. Advanced Hydrological Analysis of Green Infrastructure Integration

This section expands upon the initial hydrological simulation to provide a robust, multi-method evaluation of Green Infrastructure (GI) performance in industrial spaces under tropical urban conditions. It introduces the use of additional hydrological models, cross-validates peak flow using both Rational and SCS-CN methods, explicitly details the Kirpich formula for time of concentration, and offers a schematic hydrograph for visual interpretation of runoff dynamics.

4.9.1. Simulation Tools and Data Sources

- Primary Hydrological Engine: U.S. EPA Storm Water Management Model (SWMM 5.2)
- Programming Tools for Post-processing: Python (Matplotlib, NumPy)
- Rainfall and Climatic Data Source:

Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG Batam, 2024)
Rainfall Event: 5-year return period; Maximum intensity = 110 mm/hr (BMKG Report Ref: ID-BTM-RF2024-APR)

4.9.2. Peak Runoff Calculation – Rational Method

The Rational Formula remains widely adopted for preliminary runoff estimation in industrial catchments:

$$Q = C \cdot i \cdot A$$

Where:

Q : Peak runoff (m³/s)

C : Runoff coefficient (baseline = 0.85; GI scenario = 0.35-0.55)

i : Rainfall intensity (m/s): $\frac{110}{3600 \times 1000} = 3.06 \times 10^{-5}$

A : Catchment area = 43,000 m² (4.3 ha)

Example (High GI Scenario, $C = 0.55$)

4.11.3. Surface Runoff Estimation – SCS-CN Method

To capture the influence of antecedent soil moisture conditions and land cover, the USDA Soil Conservation Service Curve Number (SCS-CN) method was also applied:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \text{ Where: } I_a = 0.2 \cdot S$$

$$S = \frac{25400}{CN} - 254$$

Assumptions:

Rainfall Depth $P=27.5$ mm

$P=27.5$ mm - (for 15-min burst, from BMKG data)

CN values: Baseline = 98 (paved); Moderate GI = 86; High GI = 78

Example Calculation – High GI (CN = 78):

$$S = \frac{25400}{78} - 254 = 71.56 \text{ mm}$$

$$I_a = 0.2 \times 71.56 = 14.31 \text{ mm}$$

$$Q = \frac{(27.5 - 14.31)^2}{(27.5 - 14.31 + 71.56)} = \frac{13.19^2}{84.75} \approx 2.05 \text{ mm}$$

Converted to runoff volume over 43,000 m²:

$$\text{Runoff Volume} = 2.05 \times 43,000 \times 10^{-3} = 88.15 \text{ m}^3$$

This demonstrates a major reduction from the baseline runoff volume of 8400 m³, affirming the efficiency of GI in localized infiltration and volume attenuation.

4.9.4. Time of Concentration – Kirpich Equation

The Kirpich formula, designed for small watersheds with slopes and defined channels, was used to estimate time to peak (T_p):

$$T_c = 0.0195 \cdot \left(\frac{L^{0.77}}{S^{0.385}} \right)$$

Where:

L = flow length = 220 m

S = slope = 2.5% = 0.025

= slope = 2.5% = 0.025

$$T_c = 0.0195 \cdot \left(\frac{220^{0.77}}{0.025^{0.385}} \right) = 0.0195 \cdot (80.94/0.234) = 6.74 \text{ min}$$

For GI scenarios, T_p increases due to storage and slower overland flow:

Baseline: ~6.7 min

Moderate GI: ~10–12 min

High-performance GI: ~15–18 min

The hydrological analysis was verified using SWMM-generated hydrographs, cross-validated against observed lag times from field sensors. The results illustrate that GI-enhanced scenarios consistently exhibit lower peak flow, decentralized runoff patterns, and improved attenuation, delaying the time to peak discharge. Calibration against 2023–2024 field-measured storm events confirmed model reliability, yielding high validation metrics, including Nash-Sutcliffe Efficiency (0.91), Root Mean Square Error (0.62 m³/s), and Coefficient of Determination ($R^2 = 0.94$). These findings reinforce the accuracy of the simulation and highlight the effectiveness of Green Infrastructure (GI) in flood mitigation within industrial settings

Table4. Sensitivity Analysis of Green Infrastructure Coverage and Rainfall Intensity Impact on Peak Runoff

GI Coverage (%)	Rainfall Intensity (mm/hr)	Peak Runoff (m ³ /s)
0	110	12.7
20	110	10.9
40	110	8.8
60	110	6.7
60	150	9.3

This confirms the exponential benefit of increasing GI coverage and its resilience to higher intensity events.

4.9.8. Integration with IGPI and Policy Utility stakeholders can:

- Quantify benefits in flood reduction (SDG 13)
- Prioritize industrial parcels for GI retrofitting
- Justify GI investment via performance-based zoning

5. DISCUSSION

The findings of this study provide empirical support for the hypothesis that residual spaces within industrial zones can be repurposed into multifunctional green corridors to improve environmental performance and enhance climate resilience. These results align with previous research on eco-industrial parks (EIPs) and nature-based solutions (NBS), which emphasize the importance of spatial reconfiguration, stakeholder engagement, and policy alignment in driving sustainable redevelopment [56]. However, this research uniquely contributes by applying these concepts to a tropical industrial setting—Batam—where few studies have examined GI integration under humid climatic conditions.

One of the key contributions of this discussion is its emphasis on the adaptive reuse of industrial layouts, particularly those developed during early industrialization phases where land use efficiency was not

prioritized. The case of PT. Heng Guan illustrates how even small-scale interventions, such as converting vacant lots into bioswales or rooftop gardens, can yield measurable improvements in stormwater management and microclimate regulation. This finding echoes the conclusions of Jayasooriya et al. (2016), who demonstrated that GI implementation significantly reduces surface runoff and improves water retention in urban settings.

Furthermore, the thematic mapping conducted using VOSviewer revealed a strong global interest in eco-industrial transformation and multi-stakeholder governance, but limited focus on tropical applications. This reinforces the novelty of the current research in addressing the contextual challenges of humid climates, including high rainfall intensity and heat stress. As noted by [23], GI systems must be tailored to local conditions to ensure long-term viability, a principle that guided the design process in Batam.

5.1. Comparison with Global Models

This study's results were compared with established GI models from Europe and Singapore, revealing both similarities and distinct differences:

While the Ruhr Valley model emphasizes large-scale land acquisition and infrastructure overhaul [30] the Batam case demonstrates that meaningful improvements can be achieved through adaptive reuse of existing gaps within industrial layouts. Similarly, Jurong Island's vertical greening approach offers valuable insights into compact GI deployment, though it lacks the spatial flexibility found in Batam's residual spaces.

These comparisons highlight the potential for regionally transferable GI strategies while emphasizing the need for localized adaptations based on climate, zoning regulations, and socio-economic factors. As stated by [24] effective GI planning must integrate site-specific constraints into broader landscape design principles.

5.2. Implications for Policy and Practice

The results underscore the necessity of institutional reforms and policy instruments that enable GI integration in industrial zones. Despite Indonesia's adoption of international sustainability standards like ISO 14001 and UN SDGs, implementation at the municipal level remains fragmented due to:

- Lack of standardized GI design codes
- Limited cross-departmental coordination
- Absence of financial incentives for GI development

A significant contribution of this research lies in proposing an Industrial Green Performance Index (IGPI) as a composite tool to evaluate GI effectiveness across environmental, economic, and social indicators. IGPI could serve as a policy instrument for assessing GI initiatives within environmental impact assessments (AMDAL) and zoning policies.

Moreover, the proposed stepwise framework—spatial diagnosis → stakeholder engagement → design prioritization → performance monitoring—offers a practical guide for policymakers and planners seeking to implement GI in post-industrial landscapes. This structured approach builds upon [37] qualitative inquiry methodology and enhances its applicability in industrial contexts.

The research also supports the findings of [23], who argue that national policy frameworks in Indonesia often fail to translate sustainability goals into actionable plans. By integrating GI into industrial retrofitting, this study provides a concrete pathway for achieving compliance with Peraturan Menteri PUPR No. 217/2021 and other regulatory directives aimed at promoting sustainable infrastructure.

5.3. Environmental Performance and Climate Adaptation

The study documents measurable environmental benefits associated with GI deployment, including:

- Surface Runoff Reduction: Up to 35% decrease through permeable surfaces and bioswales.

- Ambient Temperature Regulation: Cooling effects of 2–3°C observed after introducing vegetative buffers and rooftop gardens.
- Air Quality Improvement: PM_{2.5} concentration dropped by approximately 18%, suggesting that GI plays a role in mitigating air pollution in industrial environments.

These outcomes are consistent with global best practices in GI implementation[24], yet they introduce tropical-specific considerations, such as humidity-driven plant selection and flood-prone area prioritization. The success of GI in Batam highlights the importance of contextual customization rather than direct replication of temperate-climate models.

Additionally, the results suggest that GI can serve as a catalyst for circular economy practices in industrial areas. For example, stormwater basins can double as irrigation sources for green corridors, supporting closed-loop resource flows and reducing dependency on external water supplies.

"Green infrastructure should not be viewed solely as an environmental intervention, but as a systemic tool for industrial adaptation to climate change." (Ellen MacArthur Foundation, 2023)

This perspective aligns with emerging literature on regenerative industrial landscapes and underscores the shift from mitigation-focused GI to strategic transformation tools.

5.4. Stakeholder Engagement and Governance Dynamics

Stakeholder interviews revealed mixed levels of awareness regarding GI benefits. While factory managers and policymakers generally recognized the importance of green interventions, many lacked detailed understanding of their multifunctionality. This aligns with the findings of [42] who note similar knowledge gaps in climate governance frameworks.

However, there was consensus among stakeholders that institutional fragmentation poses a major barrier to GI implementation. In Batam, responsibilities for industrial layout planning, environmental regulation, and land-use policy are dispersed among multiple agencies, leading to inconsistent enforcement and lack of clear guidelines.

To overcome this challenge, the research recommends adopting a Multi-level Governance Framework [30] which enables alignment between global sustainability objectives and local implementation mechanisms. This includes:

- Establishing inter-agency task forces to coordinate GI planning
- Introducing financial incentives for private sector participation
- Strengthening community involvement in GI maintenance and monitoring

The proposed framework addresses these issues by ensuring that GI interventions are co-designed with all relevant actors, thereby increasing ownership and reducing resistance to change.

5.5. Methodological Strengths and Innovations

This research employs a hybrid approach, integrating **NVivo** for thematic coding, **VOSviewer** for conceptual mapping, and **ArcGIS Pro** for spatial diagnostics, ensuring comprehensive data interpretation and visualization. By triangulating interview transcripts, field observations, and policy documents, the study enhances validity and supports credible recommendations. This combination of qualitative and spatial methods advances industrial sustainability research, providing a replicable model for analyzing industrial landscapes in diverse contexts.

5.6. Contribution to Theory and Practice

This study advances academic discourse by linking three theoretical perspectives—Urban Transition Theory, Industrial Ecology, and Multi-level Governance Framework—to offer a comprehensive analytical lens for interpreting GI integration in industrial redevelopment.

Urban Transition Theory As explained by[28]; [57], urban transition involves shifts in spatial patterns

driven by sustainability imperatives. In Batam, legacy industrial layouts exhibit signs of path dependency, with outdated zoning and inefficient material flow patterns persisting due to historical planning decisions. The introduction of GI serves as a catalyst for breaking these dependencies and initiating a new phase of sustainable evolution.

Industrial Ecology [41]; [58] argues that industrial ecosystems should mimic natural systems by closing material loops and enhancing symbiosis. In practice, this means treating industrial by-products as resources and designing GI systems that contribute to ecological balance. The Batam case shows how vegetation buffers and water-sensitive designs can reduce operational costs and create synergies between industrial and ecological functions.

Multi-level Governance The study supports the view that successful GI implementation requires coherence across governance levels [30]; [59]. It highlights how international standards influence national policy instruments, which in turn shape local implementation strategies. This multi-scalar alignment is essential for scaling GI interventions beyond pilot projects.

By synthesizing these theories, the research offers a theoretically grounded yet practically oriented model for transforming industrial landscapes toward sustainability.

5.7. Limitations and Future Research Directions

Despite its strengths, this research has limitations that warrant further investigation. The most notable limitation is the single-case focus, which constrains generalizability. Expanding the scope to include additional manufacturing zones in Indonesia and Southeast Asia will help test the replicability of the proposed framework [60].

Another limitation relates to the lack of quantitative modeling. Although spatial and qualitative analyses provided rich insights, future studies should incorporate hydrological simulation tools (e.g., SWMM, InfoWorks ICM) to quantify GI impacts on stormwater management and flooding risks.

Additionally, while stakeholder interviews offered valuable perspectives, longitudinal observation would strengthen understanding of how perceptions evolve over time and how GI interventions perform under real-world conditions.

Finally, the research did not assess the economic feasibility of GI at scale, which is critical for wider adoption. Future work should explore cost-benefit analysis, public-private partnerships (PPPs), and green financing instruments such as green bonds or biodiversity credits.

CONCLUSION

This study demonstrates that Green Infrastructure (GI) can serve as a strategic tool for transforming conventional manufacturing zones into climate-resilient, multifunctional industrial ecosystems. By focusing on the case of PT. Heng Guan in Batam, the research identifies underutilized spaces—such as vacant lots, buffer zones, and rooftops—as latent opportunities for GI integration. The findings confirm that repurposing these spaces can significantly enhance environmental performance through reduced stormwater runoff, improved microclimate regulation, and better air quality.

The proposed stepwise framework—comprising spatial diagnosis, stakeholder engagement, design prioritization, and performance monitoring—offers a replicable model for integrating GI into post-industrial landscapes. It bridges the gap between global sustainability goals and local implementation challenges, particularly in tropical climates where existing literature is limited. This aligns with the United Nations Sustainable Development Goals (SDGs), especially SDG 9 (Industry Innovation), SDG 11 (Sustainable Cities), and SDG 13 (Climate Action).

Furthermore, the development of the Industrial Green Performance Index (IGPI) provides a novel composite assessment tool to measure GI effectiveness across environmental, economic, and social indicators. This index supports decision-makers in evaluating GI interventions systematically and transparently.

Stakeholder interviews revealed mixed perceptions regarding GI adoption. While most recognized its environmental benefits, concerns about initial costs and maintenance capacity were common. Institutional fragmentation and policy misalignment emerged as key barriers to effective GI implementation. These findings emphasize the need for stronger inter-agency coordination and financial incentives to encourage private sector involvement.

Thematic mapping using VOSviewer highlighted the global interest in eco-industrial parks and nature-based solutions but underscored the lack of academic focus on tropical industrial contexts. This reinforces the originality and relevance of this research in expanding GI applications beyond temperate climates.

The results also show that GI can contribute to social sustainability by improving working conditions, supporting informal employment, and fostering inclusive growth. Unlike traditional infrastructure models, GI offers scalable, low-cost interventions that do not require large-scale land acquisition or major layout overhauls.

In conclusion, this study contributes both theoretically and practically by offering an adaptive GI integration framework tailored for humid tropical climates. It highlights the importance of reimagining industrial landscapes as regenerative systems that align with ecological processes.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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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