Integrating Life Cycle Assessment and System Dynamics in Industrial Land Preparation: A Literature Review Approach

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ABSTRACT

Industrial estate development in Indonesia plays a crucial role in driving economic growth, yet faces significant sustainability challenges, particularly during the land preparation phase, which involves clearing, leveling, backfilling, and basic infrastructure development. These activities often lead to carbon emissions, land degradation, and ecosystem disruption. Life Cycle Assessment (LCA) methods are widely used to quantitatively measure environmental impacts, such as energy consumption and greenhouse gas emissions, but are static and less able to capture socio-economic dynamics. In contrast, System Dynamics (SD) excels at dynamically modeling variable interactions and evaluating long-term policy scenarios, although it requires valid data. This article reviews previous research and emphasizes the relevance of LCA–SD integration as a comprehensive assessment framework. This integration can quantify environmental impacts while simulating policy scenarios, making it relevant to supporting more sustainable industrial estate development in Indonesia.

Keywords: Life Cycle Assessment (LCA), System Dynamics (SD), sustainability assessment, land preparation, industrial estate development

INTRODUCTION

Sustainable development is a strategic issue in global policy, emphasizing the balance between economic growth, environmental protection, and social welfare. In Indonesia, the construction sector and industrial estate development are growing rapidly as economic drivers. Industrial estates play a vital role in attracting investment, accelerating industrialization, and providing employment. However, the process of industrial estate development is not free from significant challenges, particularly in the land preparation stage, which involves clearing vegetation, leveling, land filling, and building basic infrastructure. These activities often ignore the principles of sustainability, resulting in serious impacts such as land degradation, increased carbon emissions, ecosystem disruption, and a decline in the quality of natural resources [1], [2], [3].

Previous studies have shown that land development significantly contributes to increased carbon emissions. Research [3] found that every 1% increase in the land misallocation index in China increases carbon emissions by 0.502%, with approximately 16.28% of this mediated by changes in industrial structure. Research [4] in Ethiopia shows that sustainable land management practices can reduce soil erosion while increasing land productivity. Meanwhile, a study [5] in the Indonesian context emphasizes the importance of post-mining industrial area planning that considers environmental and social risks. These facts show that sustainability in industrial area land development is not only related to environmental impacts, but also has long-term economic and social consequences.

In the context of sustainability assessment, the Life Cycle Assessment (LCA) method is widely used to assess the environmental impact of a system throughout its life cycle, from raw material extraction to the final stage of waste management. LCA allows for quantitative evaluation of greenhouse gas (GHG) emissions, energy consumption, resource utilization, and waste generation [6], [7], [8], [9]. For example, a study [10] on the South African cement industry showed that without mitigation

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policies, CO_2 emissions could double by 2040. The study [11] also emphasized the importance of developing life cycle sustainability assessment as an integrative framework for the construction sector. However, while LCA excels in providing quantitative data, this approach is static and less able to capture the complex dynamics that arise from changes in technology, policies, or socio-economic behavior.

On the other hand, System Dynamics (SD) is a modeling method that emphasizes cause-and-effect relationships, feedback loops, and time delays in complex systems. SD is effective for simulating long-term dynamics, testing variable sensitivity, and evaluating policy scenarios. Various studies have utilized SD in sustainable development issues, such as supply chain management, construction safety, and project delay mitigation [12], [13], [14], [15]. The advantage of SD lies in its ability to describe the multidimensional relationships between environmental, economic, and social aspects. However, a limitation of SD is the need for valid data for model calibration, which is often difficult to obtain.

Considering the strengths and limitations of each method, the integration of LCA and SD is relevant for assessing the sustainability of infrastructure development, including land development for industrial areas. LCA provides a quantitative overview of environmental impacts, while SD complements it with the ability to simulate long-term socio-economic dynamics and policies. Several international studies have begun to apply this integration, for example [6], [16], and [17] which assessed construction waste management, and [10] on the cement industry in South Africa. Their research results demonstrate that LCA–SD integration can explore various policy scenarios, such as the use of environmentally friendly materials or the implementation of a carbon tax, thus supporting the formulation of more sustainable development strategies.

However, to date, research on LCA-SD integration has been limited to the energy, waste, and construction materials sectors, while its application to industrial land development remains rare. Yet, decisions made in the early stages of land development will significantly determine the future sustainability of industrial areas. This research gap needs to be filled, particularly in the context of Indonesia's aggressive development of new industrial areas.

RESEARCH METHODS

This article uses a literature review approach to deeply examine the integration of Life Cycle Assessment (LCA) and System Dynamics (SD) in evaluating the sustainability of infrastructure development, with a focus on the land preparation stage of industrial estates. This literature review was chosen because the research is still at the conceptual stage, so the emphasis is directed at the exploration, analysis, and synthesis of relevant previous research. The literature sources used include reputable international journals, conference proceedings, dissertations, technical reports, international standards such as ISO 14040 concerning LCA principles, and industrial estate development policy documents in Indonesia. To enrich the perspective, case study reports from various sectors were also considered. The literature selection was carried out using the following main keywords: Life Cycle Assessment (LCA), System Dynamics (SD), LCA–SD integration, sustainability assessment, land preparation, and industrial estate development.

The study procedure was conducted systematically through five stages. First, literature identification, namely the collection of publications relevant to the topics of LCA, SD, and the integration of the two in the context of sustainable infrastructure development. Second, literature selection, namely screening based on relevance and credibility criteria. Only publications that emphasize the issues of sustainability, environmentally friendly construction, or industrial area land development and published by reputable journals or official institutions were selected. Third, literature classification, by grouping the study results into three main categories: (1) research that applies LCA to measure environmental impacts, (2) research that uses SD in modeling socio-economic-environmental dynamics, and (3) research that integrates LCA–SD to support the formulation of development policies. Fourth, thematic analysis, namely a review of the strengths, limitations, main findings, and contributions of each study, while identifying research trends, knowledge gaps, and opportunities for model development. Fifth, synthesis, namely the preparation of an integrative LCA–SD conceptual framework that can be used as a basis for further research related to industrial area land development.

To maintain focus, this study has a limited scope. The analysis is directed primarily at land development for industrial areas, although literature from other sectors such as energy, waste, and construction is still used as comparative material. This study also emphasizes LCA–SD integration, so other evaluation methods such as risk analysis or pure economic analysis are not discussed in depth. The literature used is focused on publications within the last ten years (2015–2025), with the exception of relevant classical literature, for example [19] on the basic theory of SD and [20] on the principles of LCA.

The validity of the study is maintained through source triangulation, namely by comparing research results from various sectors and geographic contexts to enrich the understanding of the potential and limitations of LCA–SD integration. A critical analysis is also conducted on the methodology, assumptions, and limitations of each previous study to ensure that the resulting synthesis is not merely descriptive, but provides a strong conceptual contribution. Finally, the results of this study are synthesized into an integrative LCA–SD model framework that can be applied in evaluating the sustainability of industrial estate land development stages in Indonesia. With this methodological approach, the article is expected to provide a comprehensive overview of previous research developments, highlight existing research gaps, and offer directions for the development of a more applicable LCA–SD model to support sustainable industrial estate development.

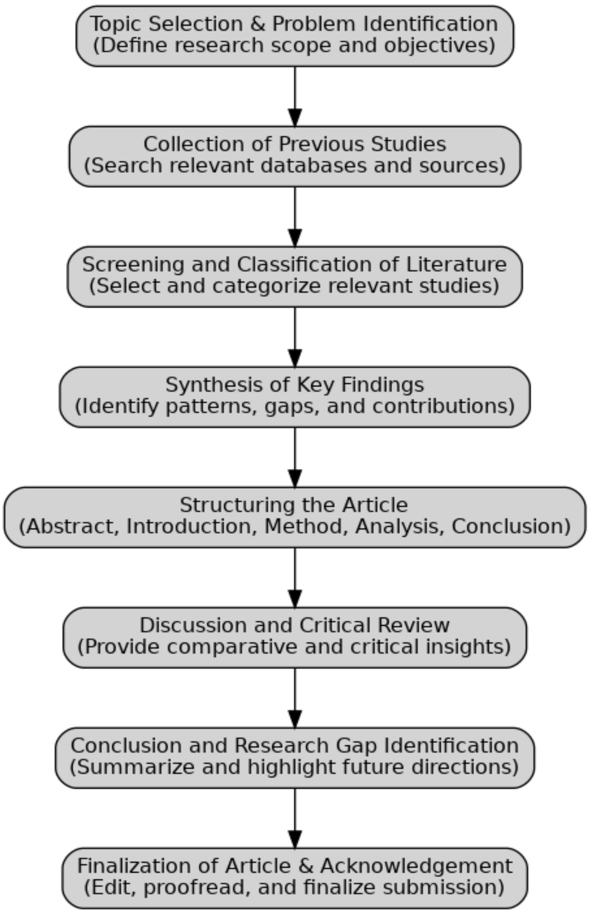

Figure 1. Flow chart

RESULTS AND DISCUSSION

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A literature review on the application of Life Cycle Assessment (LCA), System Dynamics (SD), and their integration shows rapid development in the last two decades. LCA has long been used to assess environmental impacts throughout the life cycle of a product, material, or infrastructure system, while SD is recognized as a powerful approach to understanding the dynamics of complex systems through feedback mechanisms and time delays. The integration of the two opens new opportunities in evaluating development sustainability, including at the land preparation stage of industrial areas, which is a critical phase in regional development. This section will discuss previous research trends, methodological challenges, development opportunities, and the relevance of LCA–SD integration, particularly in the Indonesian context.

LCA Research Trends in Sustainable Development

Literature review shows that the application of LCA in the construction sector and industrial areas has made a significant contribution to the understanding of environmental impacts. Research [8] shows that the use of LCA from the planning stage can reduce energy consumption and greenhouse gas (GHG) emissions through the selection of more efficient materials and technologies. This is reinforced by [7] which compared conventional concrete with geopolymer concrete based on industrial waste. The study found that geopolymer concrete can reduce GHG emissions by up to 40%, proving that material design decisions have direct implications for long-term sustainability.

In the context of industrial area development, a study [10] on the cement industry in South Africa shows that without mitigation policies, CO_2 emissions could double by 2040. By using LCA, this study emphasizes the urgency of mitigation policies in the form of the use of environmentally friendly cement, energy efficiency, and fiscal instruments such as carbon taxes. This indicates that LCA is not just a technical tool, but also supports the formulation of pro-environmental public policies.

Another study by [6] on biomass as an alternative energy source demonstrates another aspect of LCA, namely its ability to identify environmental trade-offs. While biomass has the potential to reduce carbon emissions, increased land requirements can actually trigger deforestation. This finding suggests that LCA is effective in highlighting risks that may be hidden behind sustainable technological innovations.

Table 1. Summary of previous research related to the application of Life Cycle Assessment (LCA), System Dynamics (SD), and LCA–SD integration

Author (Year)	Method	Research Context	Key Findings
Barbhuiya & Das (2023)	LCA	Building construction	LCA from the design stage can reduce energy consumption and GHG emissions through the selection of efficient materials.
Luca et al. (2023)	LCA	Conventional concrete vs geopolymer	Industrial waste-based geopolymer concrete can reduce GHG emissions by up to 40%.
Ige et al. (2022)	LCA	South African cement industry	Without mitigation policies, CO_2 emissions could double by 2040; LCA supports strategies such as blended cement, energy efficiency, and carbon taxes.
Yi et al. (2023)	LCA	Biomass energy	Biomass reduces carbon emissions, but risks increasing deforestation due to land requirements.
Nabi et al. (2020)	Elementary School	Construction safety	The SD model shows the relationship between worker compliance, work environment, and management policies on accident rates.

Author (Year)	Method	Research Context	Key Findings
Sutantio et al. (2022)	Elementary School	Indonesian construction projects	Social factors such as communication and payment are as important as technical factors in project delays.
Edalatpour et al. (2025)	Elementary School	Sustainable construction supply chain	The policy of using local and recycled materials increases energy efficiency and lowers operational costs.
Yi et al. (2023)	LCA–SD	Italian construction waste	LCA–SD integration assesses carbon emissions while modeling changes in community behavior and recycling policies.
Ige et al. (2022)	LCA–SD	South African cement industry	LCA–SD integration evaluates the long-term impacts of carbon tax policies and the use of environmentally friendly cement.
Yi et al. (2025)	LCA–SD	Construction waste	LCA–SD integration explores recycling scenarios with the support of incentive policies.
Chen et al. (2025)	LCA–SD	Construction waste	Upcycling of construction waste through LCA–SD shows the potential to reduce emissions and increase resource efficiency.

Thus, LCA has become an important method for evaluating development sustainability. However, a fundamental weakness of LCA is its static nature—focusing more on ex-post conditions—making it less able to capture the dynamics of policies, market behavior, and evolving socio-economic factors.

Developments in SD Research in Infrastructure and Environment

Unlike LCA, the SD approach allows modeling interactions between variables and exploring long-term impacts through simulation. Research [12] used SD to analyze the causes of workplace accidents in construction projects. The results showed how worker compliance, field conditions, and management interventions dynamically influence each other in influencing accident rates.

In Indonesia, [13] utilized SD to identify factors of construction project delays. The study found that social factors such as communication between parties and payment delays were as important as technical factors. The SD model allows for the exploration of various intervention policies, such as accelerating budget distribution or increasing the workforce, and projecting their impact on project completion.

Research [18] even shows that SD can be applied to sustainable construction supply chains. By modeling material flows, costs, and environmental impacts, the study found that utilizing local and recycled materials is not only environmentally friendly but also more cost-effective.

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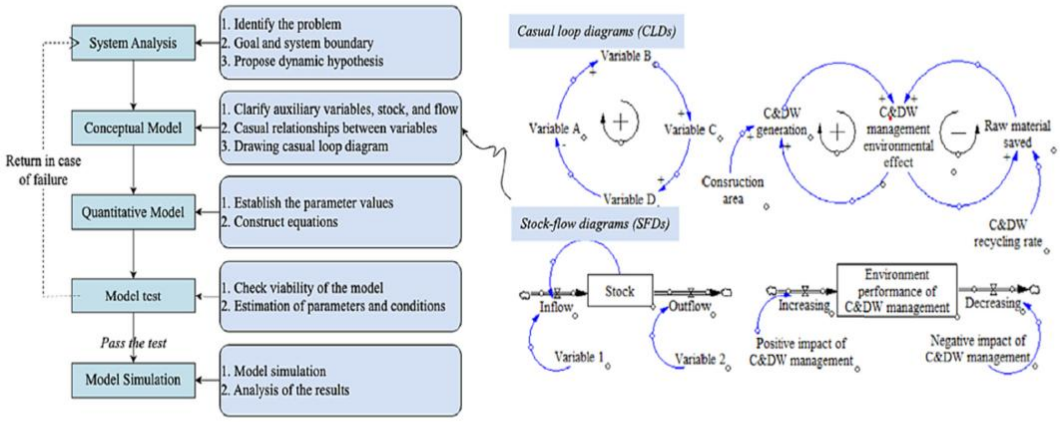

Figure 2. System Dynamics (SD) Framework

SD thus excels at exploring policy scenarios, although it relies on assumptions and data quality. If the data is less than valid, simulations can produce bias, making model validation crucial.

LCA–SD Integration as a Comprehensive Approach

LCA–SD integration offers a more comprehensive evaluation framework by combining the quantitative advantages of LCA and the predictive-dynamic capabilities of SD. Research [6] integrated the two in a study of construction waste management in Italy. The results not only calculated carbon emissions from a recycling scenario, but also modeled how changes in community behavior and government policy support influenced the success of the scenario.

Research [10] also adopted LCA–SD integration to assess mitigation policies in the cement industry. The results showed that carbon taxes can be effective in reducing emissions, but require compensation strategies to maintain industrial competitiveness.

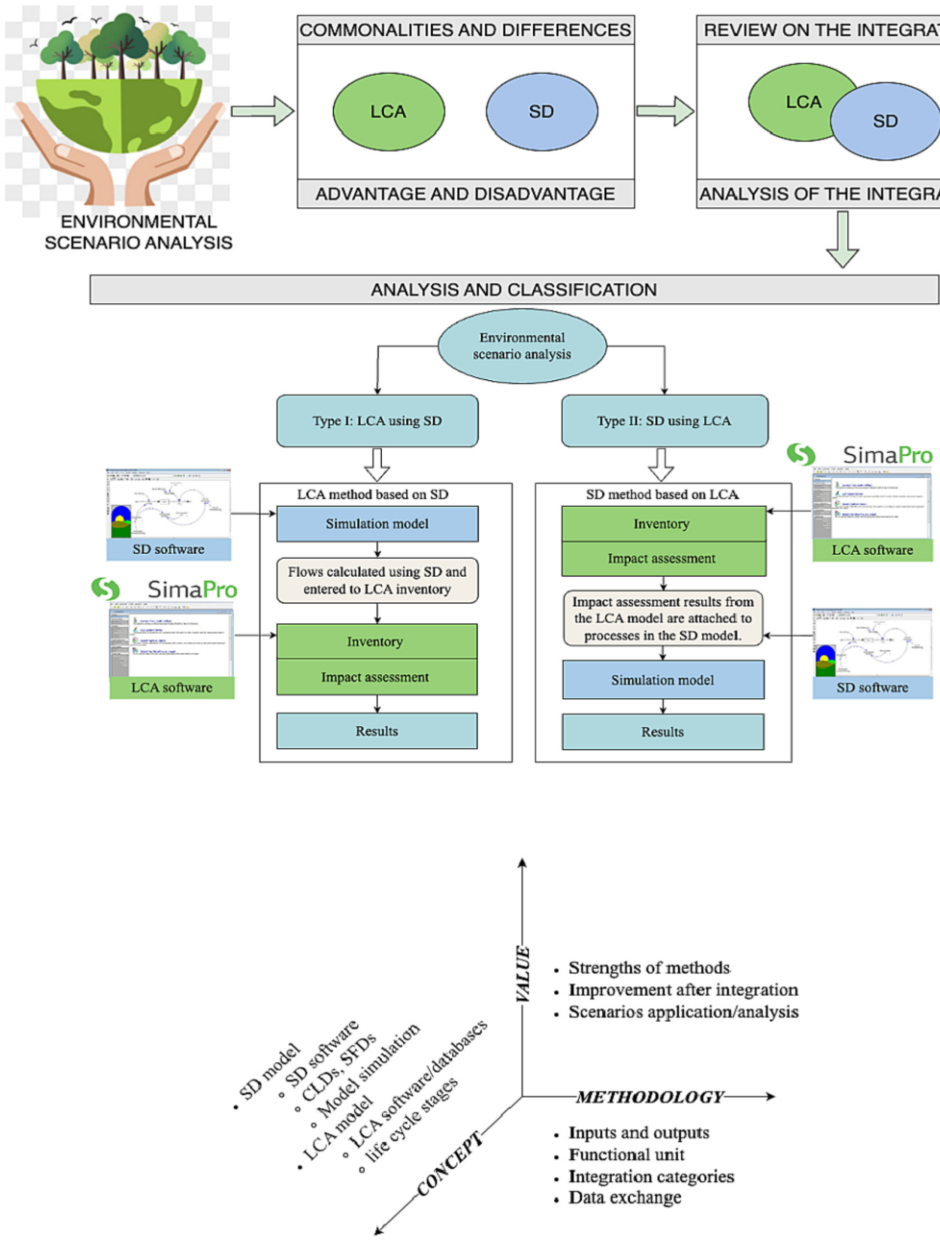

Figure 3. Three-Dimensional Framework of Variables in Integrated Analysis between System Dynamics (SD) and Life Cycle Assessment (LCA)

Through this integration, previous research has succeeded in presenting evaluations that are not only technical in nature, but also include policy simulations, making them a more relevant analytical tool for sustainable development.

Development Challenges and Opportunities

Despite its great potential, LCA–SD integration faces challenges. First, high data requirements: LCA requires detailed quantitative data, while SD requires dynamic data across variables. Second, validation is difficult due to the large number of variables across sectors. Third, the lack of standardized methodological guidelines makes it difficult to compare results between studies.

However, the development opportunities are also extensive. First, this integration can be used to evaluate sustainable development policies such as carbon taxes, recycled materials, or renewable energy. Second, LCA–SD can be an effective communication tool for policymakers because it

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presents quantitative analysis combined with scenario visualizations. Third, this approach opens up space for multidisciplinary collaboration between engineering, environmental science, economics, and public policy.

Relevance to Industrial Area Land Development

The land preparation phase for an industrial area involves clearing, leveling, backfilling, and the construction of basic infrastructure, all of which have direct environmental impacts—from carbon emissions and land degradation to ecosystem disruption. These impacts are not only short-term but also impact the socio-economic structure of the surrounding community.

The integration of LCA–SD is highly relevant for assessing this stage. LCA can quantify immediate impacts such as carbon emissions, energy consumption, and ecosystem damage, while SD can simulate the long-term impacts of policies, such as the adoption of environmentally friendly materials, land-use regulations, or renewable energy incentives.

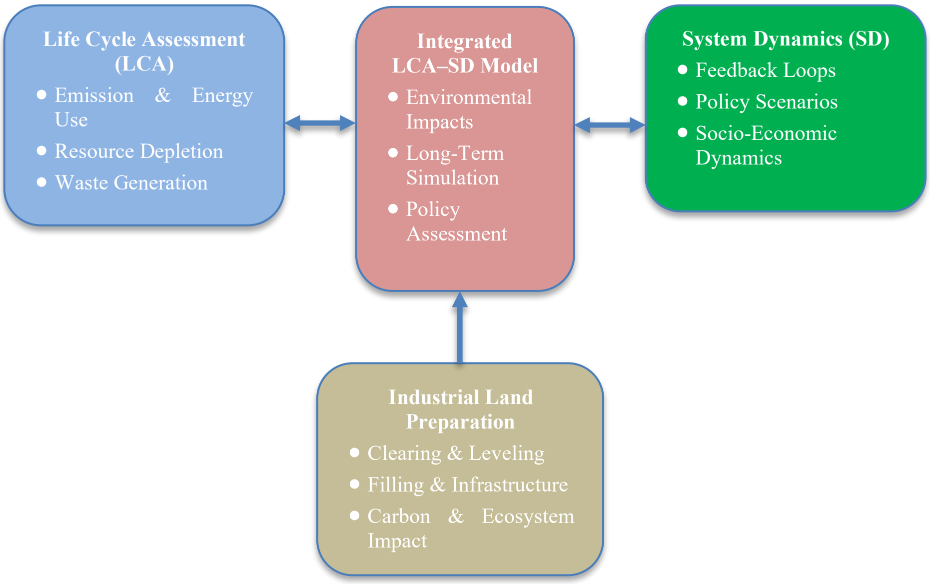

Figure 4. Conceptual Framework of LCA–SD Integrative Model for Land Maturation of Industrial Areas

In the Indonesian context, specifically the development of the Losarang Industrial Estate in Indramayu, this approach can provide a holistic picture. The integrated LCA–SD model enables policymakers to balance the needs of economic growth with environmental protection and social welfare. Thus, this integration can serve as an evidence-based policy instrument that supports the achievement of national sustainable development targets.

CONCLUSION

This literature review shows that industrial estate development, particularly during the land preparation stage, has significant environmental, social, and economic implications. Activities such as land clearing, leveling, and landfilling generate carbon emissions, ecosystem degradation, and potential long-term impacts on surrounding communities. Therefore, a more comprehensive approach to sustainability assessment is needed.

The Life Cycle Assessment (LCA) method has proven effective in quantitatively measuring environmental impacts, such as energy consumption and greenhouse gas emissions. However, LCA remains static and less able to capture socio-economic dynamics and policy changes. In contrast, System Dynamics (SD) excels at modeling complex interactions between variables and predicting long-term impacts, although it relies heavily on assumptions and data.

LCA–SD integration emerged as a comprehensive approach that combines the advantages of both. Previous studies have demonstrated that this integration can evaluate environmental impacts while simulating various development policy scenarios, making it more adaptable to the complexity of industrial systems. In the context of industrial estate development in Indonesia, the integrative LCA–SD model is highly relevant for assessing both immediate impacts and long-term projections, while supporting evidence-based policy formulation.

Thus, LCA–SD integration is worthy of development as a strategic tool in sustainable industrial area management. This model not only provides academic contributions but also offers practical benefits for governments, developers, and businesses in achieving a balance between economic growth, environmental protection, and social welfare.

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