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Life Cycle Sustainability Assessment of Bio-Based and Recycled Materials in Eco-Construction Projects

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Abstract

The construction sector is responsible for damaging the environment, using lots of energy and emitting copious greenhouse gases. As ecological issues grow, projects that use bio-based and recycled materials in buildings are becoming more popular. It gives us better ways to build by lowering the environmental impact and supporting reuse of resources. Using a Life Cycle Sustainability Assessment, this study assesses how these materials perform with regard to environmental, economic and social factors. The industry and process input-output models are included in the framework's LCSA method, which adds Life Cycle Assessment Life Cycle Costing, and Social Life Cycle Assessment. Existing case studies, EPDs and reports from companies were all sources of data used in this study. The process of economic and social assessment drew from stakeholder surveys along with market data and social hotspot databases. The research demonstrates that using bio-based and recycled materials results in less carbon emissions, less energy being used and less loss of important resources than traditional ones. Bio-based materials tend to be more expensive at first, but they give positive economic and health results over the long run. These materials encourage new job opportunities and are good for the community. The results support the idea that LCSA is essential for making environmentally friendly choices in construction and encourage using circular economy ideas in the building process.

Keywords: *Life Cycle Sustainability Assessment, Bio-Based Materials, Recycled Materials, Life Cycle Assessment, Material Performance Evaluation, Carbon Footprint Reduction.*

Introduction

Background of sustainability challenges in the construction industry

The construction industry helps drive the economy, it is responsible for around 40% of worldwide energy use and produces just over one-third of global emissions of carbon dioxide (UNEP, 2020). Many non-renewable resources like cement, steel, and concrete, which emit large quantities of CO_2 and use large amounts of energy, are used heavily in construction. Around 8% of the world's CO_2 emissions are due to manufacturing cement (Zieger, 2019). The construction industry produces a lot of waste each year and researchers found that in 2020 about 2.01 billion tons were generated (World Bank, 2021), with a lot going into landfills.

The inefficient design and construction activities in buildings commonly result in damaged habitats, less biodiversity and water contamination (Göswein et al., 2020). People continue to face problems in terms of social sustainability, such as bad working conditions, possible illness from occupational risks and uprooting from their communities due to urban development. Because construction mostly uses resources intensively, its costs are sharply affected by raw material price changes which make projects more difficult to afford and less sustainable in the latter stages (Gatto and Re, 2021). There is a strong push to build sustainably,

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through using bio-based and recycled resources, using less energy, and always keeping the entire life of the building in mind (Huang, 2021).

Rise of eco-construction and green building practices

There has been a strong movement toward sustainable and eco-friendly building in the construction sector. The goal is for these practices to help the environment during the building's whole life, including design, construction, its lifetime of use, maintenance and eventual demolition (Ghavami, 2003). Such buildings are designed with techniques that save energy, conserve water, create good indoor air, and rely on environmentally friendly materials. From the early 2000s, green buildings moved forward after international standards and certifications appeared, for example, LEED, BREEAM and Green Star (Yao et al., 2020). The criteria for these frameworks are energy usage, where materials come from, emissions, and invention, encouraging the use of green construction strategies (Vanakuru and Giduthuri, 2017).

Eco-construction uses materials that do not damage the environment, for example, composite materials, reused wood, and recycled rocks. These materials help cut down the energy involved in building and are part of a circular building approach (Tuzov, 2021). The designs that are sustainable, such as passive solar heating and green roofs, are now central to building models. Policy incentives from the government, rising consumer demand, and attention to social responsibility have made green construction spread more rapidly (Clarke, 2012).

Importance of material selection for sustainable construction

Building projects rely a lot on the right type of materials to achieve sustainability. Choosing what to build a structure from influences its energy use carbon impact, sustainability, interior air quality and the total amount needed to maintain it (Akadiri and Olomolaiye, 2012). Conventional materials, such as concrete, steel, and bricks, cause a lot of greenhouse gas emissions at every stage of their use. The part of concrete cement is responsible for around 8% of the annual CO_2 emissions globally (Calkins, 2008).

The less maintenance, and increased quality, sustainable products save money over their entire lifetime. Sometimes using eco-friendly options means paying more at the start, but the savings from lower energy costs can be seen in the future, and so these choices are often valid for keeping ahead in construction (Dixit et al., 2010). Ethical materials and supplies assist nearby communities, improve the working conditions of those in the supply chain and prevent unpleasant results from exposure to toxic emissions and bad air indoors. The obtaining of wood and other materials with certifications from third-party agencies is an ethical and clear way to purchase them (Ortiz et al., 2009). The proper materials is key to gaining certifications from LEED, BREEAM and Green Star, since these focus on conserving resources, reusing materials and measuring their effects throughout life (Sadineni et al., 2011).

Emergence of bio-based and recycled materials

Innovations in bio-based and recycled materials usher in a new era for sustainable construction to address the subtly urgent need for protecting the environment and continuous reuse in construction. Much research shows that using cement, steel and virgin wood leads to a large release of embodied energy, high emission of carbon and a negative effect on the environment (Alaerts et al., 2018). Bio-based and recycled materials use less energy and help to address climate change, use resources more wisely, and reduce waste. Bio-based materials come from living things such as plants, animals and microorganisms and are considered renewable.

These examples are bamboo, hempcrete, mycelium-based composites, cross-laminated timber, and straw bales. Ther is breakable, remove carbon with their production, and are commonly taken from local sources, which reduces emissions from delivering them (Mülhaupt, 2013). The hempcrete created with hemp and lime provides excellent protection from cold, manages the balance of moisture and has zero net emissions over its entire life. At the same time, recycled materials RCA, reclaimed wood, recycled plastics, and steel are growing in popularity as useful alternatives to freshly produced ones.

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Laboratory experiments have shown that the use of recycled aggregates in concrete replaces up to 30% of natural aggregates, all while maintaining the structure's stability (Álvarez-Chávez et al., 2012). The recycled plastic composites are being employed in insulation, cladding, and piping. Support for these materials is growing because of developments in material science, better awareness of harm to the environment, and green building certifications like LEED, BREEAM (Dammer et al., 2017). There are new rules and rewards from the government to encourage builders to use low-carbon options in projects. Since companies in the industry are working toward net-zero and a circular economy, using bio-based and recycled materials is important for the environment and for those firms looking ahead (Amziane and Sonebi, 2016).

Aim and significance of the study

The main goal of this research is to review Life Cycle Sustainability Assessments of bio-based and recycled materials used in eco-construction projects. The study hopes to assess the positive and negative impacts of these materials in the environment. The economy, and in society over their complete life cycle. The team tries to find the best sustainable building materials that match green standards and save resources during construction.

Literature Review

Overview of Life Cycle Sustainability Assessment (LCSA)

LCSA is a complete approach for studying how a product or system affects the environment, the economy and society from the start of raw material collection to the point of disposal (Costa et al., 2019). The process uses three basic methods: Life Cycle Assessment focusing on the environment and emissions; Life Cycle Costing measuring all the expenses throughout the life of the material or project; and Social Life Cycle Assessment studying the social and economic outcomes involved (Guinée, 2016). In the world of eco-construction, LCSA helps measure bio-based and recycled materials against traditional ones, helping to pick suitable materials and guide policy decisions (Zamagni et al., 2013). The complexity of data involved and the variety of social indicators, LCSA's holistic approach meets green building standards and helps experts to decide on sustainable ways to build (Fauzi et al., 2019).

Concepts of LCA, LCC, and S-LCA

The foundation of Life Cycle Sustainability Assessment is Life Cycle Assessment Life Cycle Costing and Social Life Cycle Assessment that help assess sustainability in all aspects: environmental, economic, and social (Arcese et al., 2018). LCA is considered the first of the three because it measures the environmental impacts, such as greenhouse gas emissions, energy use and water needed for a product at every step from when resources are extracted through to disposal (Petti et al., 2014). LCC considers the total costs of a product or process during its production. This strategy means stakeholders still make decisions that help the environment and are budget-friendly (Toniolo et al.,2020). S-LCA aims to cover the unnoticed social impacts of a product or process on workers, local people and users.

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Figure No.01: Concept of LCA, LCC and S-LCA

Previous studies comparing traditional vs. sustainable materials

Prior research repeatedly points out that the use of bio-based and recycled building materials has resulted in less environmental harm and reduced costs when compared to concrete, steel, and virgin plastic (Mohson et al., 2021). In Ding's view, architectural impacts on the environment are largest from old-fashioned building materials because they are tough to recycle and use a lot of energy to make. Hempcrete, bamboo, recycled steel and reclaimed wood do much better on carbon footprint and energy efficiency when compared with other types of materials (Simões et al., 2012). The authors found in their analysis that sustainable materials reduce the amount of global warming caused by landfilling by approximately 60%. The additional money put into sustainable materials is often recovered in the future to energy efficiency, strong materials, and less maintenance (Bribián et al., 2011). Working with recycled materials reduces the need for landfills and actions in line with circular economy principles for wider environmental gains. The research highlights using sustainable materials as a major step toward lowering the environmental impact of construction projects.

Benefits and challenges of using bio-based and recycled materials

These materials are helpful for the environment by emitting less greenhouse gases, using fewer natural resources and producing fewer construction waste products (Cardon et al., 2011). Bamboo, hempcrete and cork used for building because they are renewable, biodegradable and use less energy, while reclaimed wood, recycled steel and plastic composites create value from existing materials and lessen the use of fresh inputs (Bennich and Belyazid, 2017). They enhance the air people breathe in buildings and make buildings perform better thermally which helps keep occupants healthy and reduces the amount of energy wasted. It helps businesses save money over time by spending less to operate and by being awarded green certifications such as LEED and BREEAM which often adds value to a property (Pawelzik, et al., 2013).

The equipment is standardized and how well the material is accepted by buyers. Not all bio-based materials display the same mechanical strengths, moisture resistance or long service as regular materials. Because recycled materials may be contaminated or not processed consistently enough, they sometimes have to undergo quality control checks (Heinrich, 2019). It is typical that purchasing sustainable materials is costlier at the outset and less available, as developing their supply is rare in some regions (Mohanty et al., 2002).

Gaps in existing research

There is more interest in sustainable building, research and applications of bio-based and recycled materials do not fill many gaps. A main problem is that applying Life Cycle Sustainability Assessments that address

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all three dimensions is missing when comparing these materials to old ones. These studies deal with environmental aspects through Life Cycle Assessment fewer have added Life Cycle Costing and Social Life Cycle Assessment which has led to a limited understanding of what makes a product really sustainable. It is difficult for practitioners to judge the durability and dependability of bio-based materials because performance data is not available for long-term exposures in different climates and stressful situations.

A further issue is that there are relatively few studies specific to regions mainly in developing countries where things like supply chains. The climate and how things are built are quite different to in the Global North. The standardization and certification frameworks are not advanced, those in the industry feel uncertain. It needs to promote studies that blend materials science, economics, and social science to make sure policies and implementations are scalable. Closing these gaps is important for getting most people to use eco-friendly materials and build in a truly sustainable way.

Methodology

Selection of Research Design and Approach

This work uses a method of comparing bio-based and recycled resources to measure their life cycle sustainability in environmentally friendly construction. The research compares pre-selected options according to the environment, economy and society to determine which solution is most sustainable.

Criteria for the Choice of Materials

Assessment materials are given, bio-based and recycled because it is becoming more widely used in sustainable construction are available. The hempcrete and straw bale were included in this project as bio-based materials because they have a natural background, perform well for warmth and are now more often found in sustainable construction. Since reclaimed wood and recycled concrete are familiar substitutes in construction with benefits for the environment, they were selected as recycled resources.

Data Sources

The analysis is based on data gathered from a number of trustworthy sources. EPDs help by gathering accurate, verified details about how every material affects the environment. The text shares lessons and suggestions learned from examining real construction projects using the specified materials. The authors use life cycle databases like Ecoinvent and GaBi to make certain the inventory data is correct and complete for their analysis. Having information from several sources ensures the results are dependable and strong.

Tools and frameworks are included

In this study the writer uses OpenLCA, an open-source program that is broadly acknowledged for doing life cycle assessments. Using the ReCiPe 2016 method, all types of environmental impacts are evaluated with mid-point and end-point indicators. In line with UNEP standards, we use S-LCA to analyze social impacts.

Measures Used in Evaluation:

Assessing material sustainability relies on a group of well-developed indicators. Economic indicators for this product cover greenhouse gas emissions showing CO_2 equivalents energy used and water required over its entire lifespan. Initial material expenses, necessities for maintenance and the full cost over time are captured by economic metrics. The community's social data is gathered by counting new jobs, monitoring how safe and secure workers are, and checking how closely the company works with other groups.

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The study covers all regions across the globe

The research is centered on eco-construction in Europe and North America, places that are leaders in sustainable construction and supply reliable and open data on their green activities. Since the focused projects were residential, educational and public. The results are relevant for several kinds of construction projects. Concentrating on these areas allows for similar regulations, technological development and material availability which creates better comparisons of the research outcomes.

Results and Discussion

Environmental Performance

Carbon footprint reduction

A major advantage of eco-construction with bio-based and recycled materials is the important decrease in carbon emissions. Bio-based products, such as hempcrete and straw bale, remove carbon from the air when they are growing and hold it in the building. The use of reclaimed wood and recycled concrete helps reduce the pollution caused by getting and moving those materials at the start. The fact that these materials produce low emissions during their whole life cycle is why they are important for construction goals and match climate targets around the world.

Energy savings

Sustainable materials from sources greatly reduce the energy used over their lifespan. Recycled materials are often manufactured using less energy than the process for making new materials. These materials handle with less effort in factories and because they insulate well, they reduce the need for machines to heat and cool buildings. Choosing straw ball or hempcrete for the building's outer cover lowers the energy needed, which generally makes the structure less energy-intensive.

Resource efficiency

Bio-based and recycled items improve the use of resources and make them less likely that depend on finite resources. When materials are recycled, construction inputs last longer because they are reused instead of being thrown away. Bio-based materials are like biofuels, renewable. It reduces the need for transportation and encourages eco-friendly farming practices. The environmental harm of mining is lowered, less waste is produced, and sustainability is supported in everything the construction industry does.

Economic Performance

Initial vs. long-term costs

The first and ongoing costs of using sustainable solutions are sometimes debated. Although investing in eco-friendly technologies and materials costs more up front, the savings you earn over time often make it worthwhile. Energy-efficient lighting, using renewable sources and buying low-consumption devices slowly allow the costs of running the building to decrease. In many circumstances, governments support them even more with subsidies, reduced tax costs and lowered utility costs to strengthen their prospects for future success.

Maintenance and durability

The reason for this durability is often strong, lasting materials and careful design that stresses lasting and resourceful designs. Consequently, people using the system save on repairs, experience reduced outages and avoid frequent replacements. These buildings save money and help organizations plan their budgets more accurately, especially when working on big green or infrastructure projects.

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Lifecycle cost savings

Lifecycle cost savings include all the money spent on a product or system, starting from getting it to using it, maintaining it, and discarding it at the end even covering energy use. Adopting sustainable solutions means you need fewer materials, emit lower quantities of waste, and run things more smoothly, so you save money over the long run. The sustainable activities generally support corporate social responsibility and this improve the company's brand image and the value for stakeholders, often resulting in better financial gains in competitive markets.

Social Impact Assessment

Local employment opportunities

Many sustainable projects give local people new employment opportunities. More often, steps like creating green infrastructure and setting up renewable systems depend on the availability of people with expertise from the local area. It helps the region by creating jobs and training people to share knowledge. When local hiring and training opportunities are available, sustainable developments increase economic security, cut down unemployment and strengthen its community.

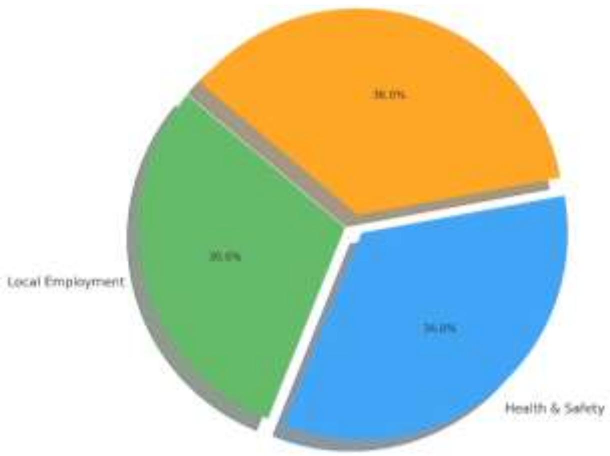
Health and safety benefits

The use of ecologically safe substances, improved technologies, and safer production methods greatly reduces the chance of people developing illnesses or being hurt by pollutants at the workplace. Green constructions and structures frequently have better air quality, light, and comfort, which benefits people's health and mood. Not only do these benefits increase how people live, but they help cut down health care costs, which favors individuals and their government.

Social acceptance and community engagement

The communities are involved in projects through conversation, taking part, and giving advice, these projects usually gain more open support and sustain their efforts for longer. Engaging people in the community helps them feel responsible, increasing the chance that they follow and support green actions. So, making sure everyone is involved in the planning process helps keep projects in line with the local culture, making sure everyone collaborates, and communities become united.

Figure No.02: Social Impact Assessment Breakdown Community Engagement



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Comparative Analysis

Traditional vs. bio-based vs. recycled materials

The average traditional material, which is affordable and easily obtained, often leads to more harm to the environment because of its excessive use of resources and energy during production. Unlike petroleum-based products, bio-based goods are better for the environment because they are biodegradable, lower carbon emissions and encourage a circular use of resources. The recycled materials play a major role in lessening waste and using less energy by taking waste from homes or industries and turning it into new goods. The costs, how well each material works, and its availability differ between materials, making it necessary to compare them when deciding.

Trade-offs and synergies across sustainability pillars

Sustainable development means dealing with different priorities and discovering how the three areas support each other. Using bio-based resources might benefit the environment, but this method is more costly or will change the way manufacturing is currently done. Sustainable products provide double profit: they aid society by making spaces safer and more comfortable, and they are more cost-effective because they last longer. Comparisons look at all factors to determine if any sustainability strategy realistically have an impact and achieved.

Case Studies

Short Summaries of 2–3 Eco-Construction Projects Using Selected Materials

To illustrate the real-world application of sustainable materials in construction, we examined three notable eco-construction projects.

Case Study 1: The Bullitt Center (USA) Often referred to as the "greenest commercial building in the world," the Bullitt Center in Seattle uses FSC-certified wood, low-impact concrete, and non-toxic finishes. Its design emphasizes energy independence, with solar panels and a rainwater harvesting system.

Case Study 2: BEDZED (UK) The Beddington Zero Energy Development in London utilizes recycled steel, reclaimed timber, and bio-based insulation. The design features high thermal mass and passive solar heating to reduce energy demands.

Case Study 3: Panyaden International School (Thailand) Constructed primarily from bamboo and adobe bricks; this project integrates local, bio-based materials with minimal environmental impact. It exemplifies how traditional techniques align with modern sustainable standards.

LCSA Application Results

Applying Life Cycle Sustainability Assessment to these projects reveals compelling insights. The Bullitt Center scored highest in environmental impact reduction, largely due to its net-zero energy performance and long-lasting materials. BEDZED excelled in social impact metrics, benefiting from community involvement and local job creation. Panyaden School demonstrated strong performance in environmental and economic dimensions, with minimal construction costs and local material sourcing minimizing embodied energy and transportation emissions. Each project highlighted a unique balance among sustainability pillars, showing how material selection directly influences LCSA outcomes.

Key Findings from Each Case

From these case studies, several key lessons emerge. First, early integration of sustainability into design and material selection yields long-term benefits across all three pillars. Second, local and recycled materials reduce environmental impact while fostering economic and social benefits. Third, there is no one-size-fits-

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all solution; each project reflects context-specific strategies that align with regional resources, climate and cultural practices. These findings underscore the importance of holistic planning and context-aware implementation in achieving sustainable construction outcomes.

Table No.02: Comparative table for eco construction case studies

Project	Materials Used	Environmental Impact	Economic Benefit	Social Impact	LCSA Score (Hypothetical)
Bullitt Center (USA)	FSC-certified wood, low-impact concrete, non-toxic finishes	High reduction	Long-term savings	Moderate	90
BEDZED (UK)	Recycled steel, reclaimed timber, bio-based insulation	Moderate reduction	Moderate savings	High (community involvement)	85
Panyaden School (Thailand)	Bamboo, adobe bricks	High reduction	High cost-efficiency	Moderate-High	88

Challenges and Limitations

Data availability and quality

Accessing data that is available and consistent is a major challenge when doing sustainability assessments. Most life cycle and social-impact databases lack important data and are linked to small-area or small-industry studies, so they cannot be dependent on for new uses. Due to a lack of recent information, those analyzing are often forced to use old or pretend data. Because of this uncertainty, the assessment might give results that people doubt, and that could bias the choices they make.

Standardization issues in S-LCA

Despite its relative newness, social life cycle assessment doesn't have a standard framework or set of measures for measuring social effects. Assessing developments differ from expert to expert; examples of measures are employment quality. The community health, and engagement with stakeholders which may each have their own way of being defined and used. No common questionnaires, scoring procedures and ways to report data make it difficult to compare research findings.

Regional differences in material performance and adoption

The maturity of supply chains and specific local expertise make material performance vary considerably from one region to another. As another example, a recycled composite meant for normal European weather wears out early when placed in tropical zones, and bio-based insulation is hard to use in locations far from agriculture. The frequency of green material use depends on enduring cultural beliefs and the strictness of environmental laws in a region. Because regions vary so much, global ratings approached locally.

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Economic constraints in developing countries

Though long-term savings are typical with sustainable materials, the high cost of initial resources and uncommon manufacturing methods often hinder use in developing countries. Without adequate financial support and weak green markets, investment is needed for urgent infrastructure and services. It may be more challenging or impossible to adopt renewable energy. The higher prices for eco-materials are a common problem in regions with limited access to subsidies and incentives. Overcoming these financial challenges calls for developer tools, structural improvements and support from laws designed locally.

Conclusion

Summary of key findings

This research reveals how Life Cycle Sustainability Assessment greatly assists in choosing materials with a positive environmental effect in construction. It becomes clear through several comparisons that bio-based and recycled materials consistently do well for the environment and overall economy much more than other traditional materials. The projects built with these materials have proven to be popular among local residents and improve health conditions, proving their full worth.

Confirmation of benefits from LCSA-informed material selection

LCSA gives experts in sustainable construction a well-structured approach for studying different aspects of the field. Using LCSA, people involved focus on the environment, the economy and the community, going past just comparing prices. LCSA helps choose materials that save emissions, preserve resources, improve living standards for communities, and maintain efficient business operations in the future.

Strategic implications for architects, policymakers, and developers

LCSA leads architects to build buildings that are adaptable, efficient, and responsible to the community. Policymakers may use these learnings to develop guidelines and rewards that motivate people to switch to sustainable materials. The developers and construction companies improve their competitive position by supporting global sustainability requirements, cutting down risks, and getting certified in LEED or BREEAM.

Contribution to circular economy and SDG

Using sustainable materials guided by LCSA helps ensure that more resources are not wasted and that the economy relies on renewables. This contributes to Goal 11 of the SDGs which demands cities be inclusive, safe, resilient, and sustainable. When materials that help maintain sustainability in the future are placed first, communities construct infrastructure that suits current times as well as those to come.

Recommendations

The Various key steps are suggested to quickly make sustainable materials more common in construction. Examples of financial incentives in policy should involve tax breaks, getting recognition for green achievements, and prioritizing projects that include bio-based or recycled materials for public projects. Standardizing assessment methods and rules support confidence and similar practices in LCSA work. LCSA into practice, it helps if urban planners and developers relate it to planning at an early design phase. It develops public-private partnerships and invests in programs that skill up construction workers. It helps to improve the quality, speed, and flexibility of evaluating sustainability in construction, making key choices for this sector more strategic and informed by evidence.

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