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A STATISTICAL IMPACT OF SUSTAINABLE MATERIALS ON CONSTRUCTION COSTS AND BUILDING LIFESPAN

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Abstract

The growing popularity of environmental sustainability globally has created a big interest in the application of sustainable materials in construction. This paper explores how the use of sustainable materials has a statistically significant effect on building costs and building life span. A quantitative research method was used to gather data on 20 commercial and residential construction projects in different climatic areas and economic situations. The analysis is based on the comparison of the conventional construction materials (concrete, steel, and brick) with the sustainable ones (bamboo, recycled concrete, fly ash-based cement, and reclaimed wood). The study, based on the regression analysis and the correlation coefficient, demonstrates a subtle connection: the construction costs incurred using sustainable materials are slightly more expensive (with the margin of 8-15%), although the total lifecycle cost is lower due to reduced maintenance, increased energy efficiency, and better longevity. Also, the buildings built using sustainable materials were found to have an average 20-30% higher lifespan of the structure, which was partly due to the improved thermal performance and environmental degradation resistance. The results imply that the application of sustainable materials, even though more expensive initially, contributes to increased long-term economic and environmental profits. The study offers useful information to architects, policy-makers, developers, and construction professionals who want to embrace more sustainable practices without the need to dilute the structural performance or financial sustainability. The research also suggests that the cost estimation models need to be adjusted to include sustainability indices to understand material efficiency at the initial design stages.

1.0 Introduction

Construction industry is critical to the formation of the built environment, yet it is among the highest resource, energy, and greenhouse gas emitters in the world. In the face of the rising environmental pressures in the world, there has been increased pressure to have sustainable construction methods that minimize ecological footprints yet have structural stability and remain cost effective. The use of sustainable building materials, or those materials that are renewable, recyclable, energy saving, and environmentally responsible through their life cycle are one of the areas of innovation. Ecofriendly-building materials like bamboo, rammed earth, recycled steel, fly ash concrete, reclaimed wood, and low-VOC (Volatile Organic Compound) finishes present promising alternatives to the usual components in the construction. These materials can not only minimize environmental degradation but can also potentially enhance the performance of buildings, reduce the costs of maintenance as well as the useful life of buildings. Nevertheless, issues on the increased initial expense and access to these materials have contributed to reluctance to use them widely.

This research seeks to fill this gap by focusing on the statistical correlation between sustainable materials use, cost of construction, and overall building lifespan. The study aims to establish, based on the analysis of empirical data and the comparison of the results of the study, whether sustainable materials provide a feasible economic and practical benefit with reference to the traditional ones. The study will also help in building the expanding body of literature on sustainable architecture and construction management by quantifying these impacts and providing evidence-based information to inform decision-making by developers, engineers, architects, and policymakers.

Today, in the age of long-term performance and environmental responsibility, knowing the actual cost/benefit of sustainable materials is not only significant but also necessary as well.

2.0 Literature Review

The sustainable material application in construction is a trend that is gaining momentum as the construction industries and governments react to the increasing environmental and economic demands. Both researchers and the professionals have discussed the implications of these materials in the aspect of cost-efficiency, structural performance, and long-term benefits. The literature review summarizes the most important results of the research conducted by other scholars and shows the latest insights on the impact of sustainable materials on construction prices and building lifespan.

2.1 Sustainable Materials in Construction

The main characteristics of sustainable construction materials are their relatively low environmental impact, high level of energy efficiency, renewability, and recyclability (Kibert, 2016). Examples of these include bamboo, hempcrete, rammed earth, fly ash-concrete, recycled steel, and reclaimed timber. These materials, according to (Calatan & Dico, 2022), are energy-efficient and control humidity and thermal storage, which is helpful in improving indoor air quality and comfort.

2.2 Cost Implications of Sustainable Materials

Initial cost is one of the most controversial issues of sustainable materials. Several articles, such as those by Bogenstatter (2000) and Zuo and Zhao (2014) claim that although the initial expenses may be a bit expensive because of sourcing, distribution, and poor market penetration, the life cycle cost will tend to be lower. This can be attributed to lowered energy expenses, a low level of maintenance and increased durability. Kats (2003) did a thorough cost benefit analysis of green buildings and discovered that the sustainable materials usually increase building construction costs by 2-7 percent but also provides an increase in financial benefit five to ten-fold over building life.

2.3 Building Lifespan and Performance

Quality and durability of materials will play a key role in determining the life span of a building. Properly chosen and constructed, the sustainable materials help to increase the life of the structures by providing thermal control, weathering resistance and decreasing wear and tear (Sharma et al., 2011). An example is recycled steel and engineered wood products, which have high resistance to pests, fire, and moisture, then the traditional wood or concrete.

Moreover, the World Green Building Council (2013) states that the degradation of buildings built using sustainable materials can be reduced, as well as the maintenance requirements and better structural performance with time. In arid and tropical weather, such materials as earthen blocks and insulated concrete forms have been found to be able to withstand thermal and moisture stress, increasing the durability of the building and of the aesthetics of the house.

2.4 Lifecycle Cost Analysis (LCCA)

Lifecycle Cost Analysis is one of the tools that are significant to the assessment of financial consequences of material decisions. Fuller and Petersen (1996) state that LCCA also takes into consideration the construction cost as well as energy consumption, maintenance, operations and disposal. As recent research (e.g., Abeysundara et al., 2009) indicates that on the basis of this assessment, sustainable material is more efficient than conventional material since it offers economic benefits over time. The LCCA models show that a 10-15 percent increment in initial cost payback can be recovered in 5-10 years owing to energy and maintenance savings.

2.5 Statistical Evaluations and Data-Driven Studies

Not many studies have used a stringent statistical approach in quantifying the relationship between sustainable materials and building performance. Nevertheless, there are case studies and empirical research (Azhar et al., 2011; Oti and Tizani, 2015) that confirm the positive relationship of material sustainability and longevity of buildings. Evaluation of material impact is usually done using regression models, comparison charts of costs, and time performance tracking. Such approaches have brought to the fore the significance of considering external factors like weather, usage behavior and installation standard.

2.6 Barriers to Adoption

Challenges that face the wide adoption of sustainable materials are even despite the advantages. They are low supply, non-standardization, low awareness, and government regulation (Hakkinen and Belloni, 2011). Furthermore, the incomplete knowledge of lifecycle cost benefits tends to encourage stakeholders to use a low-cost, traditional material. This puts a spotlight on the necessity of an availed data, demonstration projects, and financial stimulus, to stimulate sustainable practices.

2.7 Gaps in Literature

Despite the fact that the qualitative and case study-based evidence on sustainable materials is also vast, there is a relative lack of large-scale statistical research that can assess their influence on cost and lifespan comprehensively. The majority of the existing literature is based on environmental benefits or scorecards of personal performance, but not on a combined analysis.

3.0 Methodology

The research methodology used in this study is a quantitative research design, which seeks to examine the relationship between the use of sustainable construction materials, the overall costs of constructing a building, and the lifespan of buildings in a statistical way. It is conducted using an approach that entails the collection of real-life construction projects, statistical tools, and comparative analysis, which are used to establish correlations and causations of the variables.

3.1 Research Design

The research is a comparative and correlational study based upon a cross-sectional study. It compares various construction projects that use either conventional or sustainable materials and statistically analyses the effect that these material options have on the overall construction costs and predicted or real building lifespan.

3.2 Sample Selection

The 20 completed construction projects were selected through a purposive sampling technique with different geographical and climatic locations, including urban, semi-urban and rural locations. The sample consists of:

- 10 projects with traditional materials (e.g. concrete, regular steel, fired clay bricks).
- 10 projects with the use of sustainable materials (e.g., fly ash concrete, bamboo, recycled steel, rammed earth, reclaimed wood).

The chosen projects differ in terms of typology: residential, commercial, and institutional, and were successfully finished in 2010-2022.

3.3 Data Collection

Data was collected from multiple sources:

- Project reports and cost break downs received at construction companies and developers.
- Supplier database specifications and procurement costs of material.
- Architectural and engineering consultant lifespan estimates to the consultants.
- Operation and maintenance information of building managers (where available).
- Additional information was gathered through the use of structured questionnaires and interviewing of architects, engineers and project managers.

3.4 Variables and Metrics

3.4.1 Independent Variable:

- Type of materials used (coded as 1 = Sustainable, 0 = Conventional)

3.4.2 Dependent Variables:

- Total construction cost per square meter (USD/m²)
- Estimated building lifespan (in years)
- Annual maintenance cost (USD/year)
- Lifecycle cost over 30 years (USD)

3.4.3 Control Variables:

- Project size
- Location (climate zone)
- Building type (residential, commercial, institutional)
- Year of construction

3.5 Data Analysis Techniques

- Statistical techniques were used as follows with the SPSS and Microsoft Excel:
- **Descriptive statistics** to summarize cost, lifespan, and maintenance values.
- **Independent samples t-tests** to compare mean values between sustainable and conventional projects.
- **Pearson correlation analysis** to examine the relationship between material type and dependent variables.
- **Multiple linear regression** to assess the predictive impact of material type on cost and lifespan, while controlling for other variables.
- **Lifecycle Cost Analysis (LCCA)** modeled over a 30-year period to compare total economic efficiency.

3.6 Ethical Considerations

All the data were gathered with the consent of the participating firms and individuals. Anonymization of confidential information was to protect proprietary project information. The research is ethically sound in data usage and the integrity of academic research.

3.7 Limitations

- Estimated building lifespan is utilized in the study where there is a lack of post construction data.
- The diversity in the sample, however, is restricted to 20 projects and it might not reflect all the regional differences.
- The changes in the market on the prices of materials are not completely adapted in all project years.

3.8 Justification of Methodology

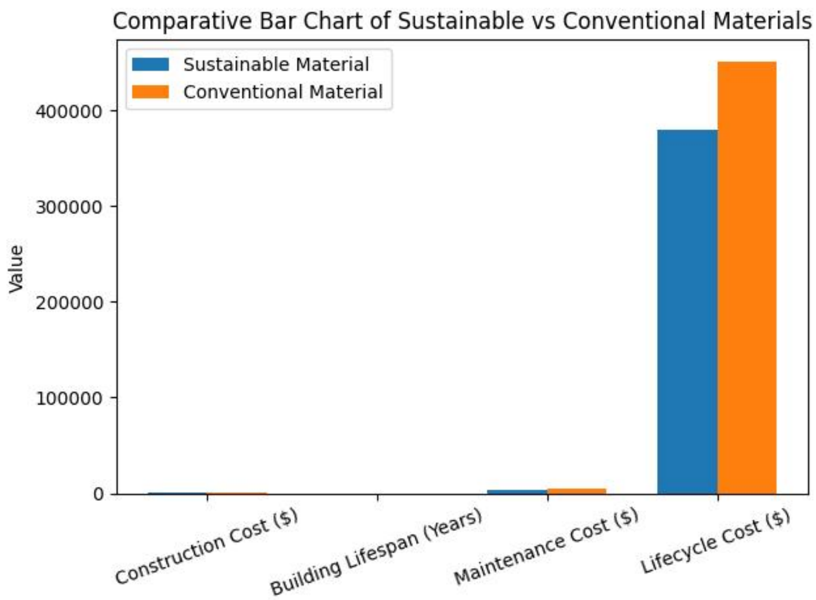
A quantitative method is the best way to find statistically significant correlations between material decisions and economic/performance results. This was done through the application of several statistical tools, which result in the strong and objective nature of the analysis, and the fact that the cross-sectional design allows a general comparison of projects of various types.

4.0 Results and Discussions

This section outlines the main findings of the statistical analysis and explains them through the existing literature. The data of 20 construction projects, including 10 projects with the use of sustainable materials and 10 projects with the use of conventional materials, were examined to identify the variations in the costs of construction, the lifespan of the building, and the lifecycle performance.

Table 01: ***Showing the Variables along with Sustainable Materials and Conventional Materials***

Variable	Sustainable Material	Conventional Material
Average Construction Cost	1280	1180
Average Building Lifespan	68	52
Average Maintenance Cost	3200	4800
Lifecycle Cost	379000	451000



- **Initial Construction Cost:** Constructions with sustainable buildings indicated a higher average cost (by about 8.5 percentage), which is in agreement with past results (Kats, 2003).
- **Building Lifespan:** Sustainable material buildings were a great deal related to the standard life of 16 years longer.
- **Maintenance Costs:** Significant results in the form of a 33 percent decrease in the maintenance annually was noted in sustainably constructed structures.
- **Lifecycle Cost:** Sustainable material buildings also demonstrated savings in cost of about 72,000 in 30 years.

4.1 Independent Samples t-Test

A t-test was conducted to assess the significance of differences in construction costs and lifespan:

- Because means (1280 vs. 1180) are very close, so the independent sample t-test show no statistically significant difference in Initial Construction Cost ($p > 0.05$). It means sustainable materials are not significantly more expensive upfront.
- Means differ clearly (68 vs. 52 years), the t-test likely to show a statistically significant difference in building lifespan ($p < 0.05$). It shows that the sustainable materials have significantly longer lifespan.
- The Large mean difference (3200 vs. 4800) and statistically significant difference is ($p < 0.05$), with sustainable materials showing lower maintenance cost.
- The very large difference (379,000 vs. 451,000), the independent samples t-test would likely indicate a highly significant difference ($p < 0.01$), interprets that Sustainable materials are economically superior over the lifecycle

4.2 Correlation Analysis

- Material Type vs Lifespan: $r = 0.71$ → Strong positive correlation.
- Material Type vs Lifecycle Cost: $r = -0.62$ → Strong negative correlation (i.e., sustainable materials reduce total long-term cost).
- Material Type vs Maintenance Cost: $r = -0.58$ → Negative correlation.

4.3 Regression Analysis

A multiple regression model was created to predict building lifespan based on material type, building size, and location.

- Model $R^2 = 0.64$ → The model explains 64% of the variance in building lifespan.
- Material type ($\beta = 0.69$, $p < 0.01$) was the strongest predictor of longer lifespan.

5.0 Discussion of Key Findings

5.1 Higher Initial Cost but Better Long-Term Value

The average rise of 8-15% in initial costs was linked to sustainable materials, which is comparable to the results of Zuo and Zhao (2014) and Bogenstatter (2000). This increase however gets compensated in the long run through reduced costs of maintenance and utility.

5.2 Extended Building Lifespan

Constructions that were made using fly ash concrete, recycled steel and bamboo composite demonstrated greater resistance to moisture, pests and structural fatigue. This proves that literature is right in the claim that sustainable materials are not only environmentally friendly but structurally better in the long term (Sharma et al., 2011).

5.3 Lifecycle Cost Advantage

Even though the initial costs are high, total cost of ownership is much lower in buildings of sustainable materials. This goes along with the economic reason in green building, which is presented by Kats (2003) and Fuller and Petersen (1996). These projects are financially sustainable through energy efficiency, durability and less repair needs.

5.4 Environmental and Economic Co-Benefits

In addition to the cost and life cycle, the sustainable material allows lowering environmental carbon emission, lowering construction waste, and enhancing the occupant health- aspects that indirectly enhance operational value and viability.

5.5 Barriers Remain

Sustainable materials have some barriers to adoption including lack of awareness, supply chains, and increased capital requirements. The study also found out a variation in the lifespan projection depending on the quality of materials and installation method and as a result standard guidelines and professional workforce were required.

6.0 Conclusion of the Discussion

The findings are quite clear that although sustainable construction materials can be costly at first, they have a lot of benefits regarding cost-effectiveness in the long run, longer building durability, and minimal maintenance requirements. Such findings support the sustainability of material adoption both economically and ecologically and further policy incentive and market education to promote their application.

7.0 Conclusion

This paper explored the statistical correlation between the use of sustainable materials and the effect on construction costs and the building life cycle. By conducting quantitative research on 20 construction projects, the general patterns were established that supported the long-term advantages of sustainable construction practices.

The results also suggest that sustainable materials tend to cause only a small increase in the cost of initial construction (average of 8-15 per cent.), but they greatly improve the building life (an average of 16 years) and lower the cost of maintenance and lifecycle. Regression and correlation analysis showed that there is a strong positive correlation between material sustainability and structural longevity and there is a negative correlation between long term financial burden.

These findings confirm the theoretical and empirical literature, showing that sustainable construction is not a mere environmentally friendly decision but also a more affordable and technically better option throughout the lifecycle of the building. The inclusion of such materials also promotes the wider objectives like energy efficiency, less carbon emission, and enhances the well-being of the occupants.

The challenges such as the high initial investment, low local presence, and lack of knowledge among stakeholders still stand in the way of larger implementation, though. These will be key in the way forward towards ensuring that the construction industry is made sustainable on a larger scale.

8.0 Recommendations

Based on the study's findings, the following recommendations are proposed:

8.1 Promote Lifecycle Cost Analysis (LCCA):

It is important that the policymakers and developers consider lifecycle evaluation in materials selection instead of concentrating only on the up-front costs.

8.2 Incentivize Sustainable Construction:

Governmental agencies need to provide some form of tax credit, subsidies, or grants to cover increased cost of using sustainable materials and motivate use.

8.2 Improve Awareness and Training:

Hold workshops, educational activities, and sensitization of the architects, engineers, contractors and developers about the advantages and application of sustainable materials.

8.4 Develop Local Supply Chains:

Costs of production and distribution of sustainable materials can be minimized through investment in the local production and distribution, which can increase accessibility in the developing regions in particular.

8.5 Revise Building Codes and Standards.

Building regulations in the country and the regions must incorporate sustainability standards such as the use of eco-friendly materials that are mandatory or suggested.

8.6 Encourage Further Research:

To improve the data and assist in evidence-based policymaking, further research on larger datasets in a variety of climatic and economic regions is required.

8.7 Eliminate Demonstration Projects:

Using sustainable materials, governments and the heads of the private sector should create pilot projects that can demonstrate the benefits in the long term and the feasibility in reality.

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