Journal Of Research Technology & Engineering
www.jrte.org
JOURNAL OF RESEARCH TECHNOLOGY & ENGINEERING

Sustainable Material Solutions for Reduced Environmental Impact

R.W.M.R.D.C.B. Rajasinghe, G.M.N.G.B.M.B. Gamlath, Udara S.P.R. Arachchige

Department of Mechatronic and Industrial Engineering, Faculty of Engineering, NSBM Green University, Homagama, Sri Lanka

rdcbrajasinghe@students.nsbm.ac.lk

Received: 15 Jun 2025; Revised:25 Jun 2025; Accepted: 04 July 2025; Available online: 10 July 2025

Abstract: Both resource usage and greenhouse gas emission problems are significant problems worldwide, and these problems emphasize the need for engineering materials for environmental sustainability. The research uses case studies and Life Cycle Assessment (LCA) to select alternative materials such as geopolymer concrete, hempcrete, recycled metals, bamboo, engineered wood and bioplastics. The tested materials align closer with circular economy principles, have a lower carbon footprint, and have lower embodied energy than conventional materials such as Ordinary Portland Cement (OPC), virgin steel, and virgin plastic. The research supports dual environmental and socioeconomic benefits as it proves carbon sequestration through energy efficiency and rural employment development through sourcing local materials. Two real Sri Lankan case examples demonstrate how earthbag housing was rebuilt after tsunamis and commercial buildings were LEED certified, showing the actual project execution. Some material costs, regulatory and material procurement, technical competitions and obstacles exist. Three innovations are explored as future solutions, including 3D printed geopolymer structures, bio fabrication insulation and innovative materials, global best practices and 'early adoption' trends. Although updated building regulations and specialized training combined with government incentives can eventually help unlock widespread implementation, it is also demonstrated that we need localized LCA information. Sri Lanka offers an effective way to take an approach that integrates sustainable materials in climate resilience development to serve in the attainment of sustainable development goals and drive an environmentally friendly green building sector. The research conducted is a reference point to provide stakeholders with a means of making choices which combine environmental conservation with technical standards and monetary factors.

Keywords: Eco-Innovation, Geopolymer Concrete, Green Engineering Education, Green Materials, Hempcrete, Life Cycle Assessment, Sustainable Engineering Materials

1. INTRODUCTION

Due to the high requirements of the future, the 21st century requires the development of infrastructure that has never been seen or heard of before, industry development, and development in the field of technologies, which need more and more material to be used in the construction of and development of buildings, and manufacturing, transportation and so on [1]. Nevertheless, this advancement is economically costly to the environment, leading to degradation, use of resources, and emission of greenhouse gases in the engineering life cycle of materials. The materials are widely used in the current society, and with them comes more and more environmental challenges to overlook.

Sustainable materials in engineering is being embraced to mitigate the environmental degradation and prudent utilization of resources. These raw materials can be obtained many times, recycled and energy efficient to prevent the damage of ecosystems in life cycle. Due to the efforts to meet global climate goals, cut down pollution, preserve finite resources, and with every country trying their best, it is no longer possible to keep them out of corporate life [2].

The emerging fields of environmental science and engineering are compelling the development of sustainable materials engineering to minimize environmental effects. Conventional resources like cement are quite polluting, energy-consuming, and CO2-producing. Conventional resources like plastics cause permanent pollution and endanger marine life and human health. These problems can be alleviated through sustainable materials engineering to foster the sustainability trend within different industries [3].

The engineering materials are sustainable and environmentally friendly, reducing carbon footprint, energy consumption, and toxicity. These are renewable materials such as bamboo, hemp, bioplastics, and other high technologies such as green concrete, recycled composite, and low-energy metals. The most important attribute of sustainable materials is that they can meet the existing engineering uses without the environment or the supply being interfered with [4].

The sustainability of the environment is an important guide in contemporary engineering. It is geared towards promoting ecological sustainability and preserving the environment by minimizing the output of greenhouse emissions and reliance on nonrenewable resources. This vision requires life and chemical engineering materials to minimize the emission of greenhouse gases and pursue a circular economy. These would be the replacement of cement constituents of concrete with fly ash or slag and the recycling of aluminum in automobiles and airplanes with recycles since only 5% of energy is consumed when compared to primary aluminum manufacturing [1],[2],[5].

Economic and social sustainability requires using sustainable materials, which have long-term energy, maintenance, and waste disposal advantages. They also increase the health and safety of the people by improving indoor and outdoor atmosphere. Civil engineering (Basement) Low VOCs clean up air, and lightweight composites in transportation networks save fuel economy and emission [7].

Sustainable engineering is a flourishing sphere with constant innovations and inventions. Technicians and researchers worldwide are developing high-technology materials to deal with environmental concerns. These are self-healing concrete, bioplastics, and phase change materials. Innovations in nanotechnology, biotechnology, and materials science research encourage innovative and adaptive materials that excel by balancing performance and being resource-efficient [6].

New inventions such as life cycle assessment (LCA), cradle-to-cradle design, and digital twins are optimizing the innovation ecosystem by measuring the environmental impact of materials during the total life cycles. This approach focuses on sustainability during material development to remove the subjectivity of material choices and synchronize them with the environmental objectives [8].

Driving Sustainable Engineering Materials: The barriers to adopting engineered materials include cost, availability, scalability, technical performance, and regulatory acceptance. Alternative materials with lower impact on the globe might not serve as well as the standard ones, and the supply chain of green materials on a global basis remains under development. The government should work with academics, industry, and society to ensure that the issue of sustainable development and the adoption of materials are prioritized as part of the policy and research agenda [9].

Raising education and knowledge is important in the transformation of engineering. Engineering students in the future ought to be prepared with technical performance, environmental, and social impact assessment. Sustainability principles, ethics, and innovation should be incorporated into engineering curricula. They are supposed to learn to help enhance diverse arts constantly. The engineering profession can enable a healthier, more resilient, and clean future through the establishment of a sustainability culture [10].

Materials selection and use in engineering are essential for health and safety since conventional materials are mostly occupational hazards and nocuous releases. Non-toxic recipes and safer manufacturing processes with so-called sustainable materials are preferred. For example, workers' and occupants' health risks are reduced when asbestos-containing material is replaced with sustainable fiber-reinforced materials. There is also the elimination of exposure to harmful chemicals through water-based adhesives [11].

The international collaboration to achieve sustainability is based on such agreements as the United Nations Sustainable Development Goals, the Paris Agreement, and the European Green Deal. These programs focus on sustainable industry, responsible consumption, climate action, and innovation. Feminine sustainable materials contribute to these objectives by boosting clean energy generation, sustainable urbanism, sustainable consumption, and adaptation to the climate. They are critical for the world's environmental protection [8],[10].

The rich resources and the emerging environmental issues in Sri Lanka are an opportunity to transform materials towards sustainability. There is a fast turnover in the construction and production sectors, all requiring sustainable materials. The application of locally available green materials, indigenous knowledge assessment components, and environmental evaluation in engineering may contribute to sustainable national development. The country has biodiversity, and therefore, the focus of the selection of materials ought to be geared towards conservation [12].

Disaster-resistant and climate adaptation in vulnerable districts rely on sustainable engineering materials. They are long-lasting, versatile, and have a low environmental impact. Permeable pavements and flood-proof buildings can control floods and pollution. Disaster relief after any accident can be done using light and modular materials [13].

Clark and Oates (2022) emphasize that the increasing role of sustainable engineering materials in the 21st century cannot be ignored. The material utilizes science, engineering, ethical conduct, and environmental consciousness, showing commitment to engineering performance and human flourishing. In the sustainable development of materials, we need to identify the challenges and as well as the opportunities that future engineers should be in a position to discover [14].

The research theory examines sustainable materials in engineering that are critical for environmental minimization and sustainable development. It explores sustainability strategies, material technologies, and best practices all over the globe to provide the means to use sustainable materials, reduce environmental impact, and expand human development needs. Sourcing materials, designing techniques, and end-of-life recycling are the significant roles of engineers and make up the future of sustainable engineering [11].

2. METHODOLOGY

2.1 Data Sources

The research relied on information from reputable and well-known sources. The work of Fernando et al. (2021) provided information on how local methods can be used in construction. According to reports from the Sri Lanka Sustainable Energy Authority and the Green Building Council of Sri Lanka, many sustainable practices and certification systems are in use today [15]. Moreover, real cases, such as using earthbag building in tsunami recovery in Sri Lanka, confirmed how sustainable materials like earthbags could be successfully applied there [16].

2.2 Material Selection Criteria

The selection of materials followed guidelines that met Sri Lanka's special needs and situation. The design process paid close attention to the environment by considering data from LCA to identify low-energy and less carbon-emitting materials [17]. Materials were favored if found nearby, allowing for lower emissions from transport and helping the nation's economy [18]. Another factor was ensuring that the materials chosen respect local customs and are appreciated by the community [18]. Decision-makers paid special attention to cost issues since designing for low-income housing required making the solutions affordable [19].

2.3 Evaluation Framework

The framework was established to provide a detailed review of materials for their sustainability. LCA was applied to measure the environmental effects of every step, from making to disposing of a material [19]. To find out if a material was ready for widespread use, the TRL was used to assess its development stage [20]. Service learning includes aging and cost analysis [21]. Furthermore, the performance, users' satisfaction, and difficulties during implementation were examined using examples from real projects [22].

2.4 Case Study Integration

Several case studies showed how sustainable materials are used in Sri Lanka. As a result of the tsunami, earthbags were used for housing, revealing that this method is suitable for environmentally friendly rebuilding [23]. In this industry, recycled products are critical, as foundries use them to make components the construction industry uses [24]. Furthermore, the green design and materials used in Access Tower II in Colombo helped it earn LEED certification and prove the profitability of green construction [25].

2.5 Life Cycle Assessment (LCA)

The study utilized LCA to evaluate the quantitative effects of material on the environment. The study implemented ISO 14040 methodology to address stages from raw material extraction to disposal completion [16]. Global warming potential, water consumption, and energy consumption formed the core impact categories in the assessment. Research data came from published LCA studies and databases to establish precision and match results [19].

2.6 Tools and Software

The researchers applied Microsoft Excel to analyze numerical data in LCA research studies. In contrast, NVivo was employed in analyzing qualitative literature appraisal and case studies analysis, which led to creating themes and synthesis. Standards of environmental impact assessment were based on LCA databases and occupied the position of the European Life Cycle Database (ELCD) EC (2018) [8].

2.7 Limitations

Literature and case study implementation leads to the research design that leaves out most of the existing materials and those that differ with the region. The trends related to the study of sustainable materials have triggered some changes owing to the high pace of changes observed. The targeted geographical area was to be reviewed in Sri Lanka. However, various data and case studies of other areas have been identified in light of the inaccessibility of data on the same area [9].

2.8 Ethical Considerations

The academic project properly referenced all resources to preserve scholarly ethical standards. The study did not gather data from human subjects since it did not need ethical approval. The research worked towards presenting an unbiased report that acknowledged both the positive aspects and difficulties of sustainable engineering materials [10].

3. Results and Discussion

This part gives you an idea of how sustainable engineering materials impact the environment, perform, are innovative, encounter challenges, and can be used in Sri Lanka.

3.1 Analysis of Sustainable Engineering Materials

Sustainable materials in engineering that have less environmental impact than ordinary ones are studied, pointing out their strengths and weaknesses along with the best uses for these materials.

3.1.1 Geopolymer Concrete

Geopolymer concrete has become the green alternative to Ordinary Portland Cement (OPC) concrete. Geopolymer binders are made by alkali activation of materials that coal power plants, the steel industry, and certain natural clay, unlike OPC, which naturally uses excessive energy and releases a lot of CO_2 when limestone is calcined. This occurs at cool temperatures, like ambient or lower than 100°C, so less energy is needed to produce the binders [13].

Using geopolymer concrete, the carbon footprint of construction materials can be lowered by 40% to 80% based on how the concrete is made. On the contrary, OPC accounts for 5-8% of CO_2 emissions from human activities. Depending on the type of geopolymer concrete used, it can have equal compressive strength to OPC and be highly solid against sulfates, acid attacks, and fires. That is why it is highly suitable for building roads and other structures involving lots of water.

It is not always easy for families to adopt. The mixture can be inconsistent because of the differences in fly ash and slag, and alkaline activators must be used with safety in mind. There is insufficient fly ash from thermal power plants or GGBS from overseas steel imports in Sri Lanka. It is necessary to look into local minerals and natural pozzolans as choices for cement. Local authorities should also invest in training their workers in mix design, handling, and quality control.

Fig 1: Geopolymer Concrete

3.1.2 Hempcrete

Hempcrete is a bio-composite mixed with hemp hurds (center of hemp stalk), lime, and water-based binder. It is a non-structural infill material for walls, floors, and roofs and needs a separate structural frame (timber, steel, or concrete). Sustainability is important in many ways [2]. Hemp is a plant that grows quickly and captures atmospheric CO_2 during its growth, essentially permanently locking carbon into that building material. The lime binder used here is carbon-intensive to produce but reabsorbs CO_2 over time by carbonation.

Hempcrete provides good thermal insulation properties and reduces energy consumption for heating and cooling the buildings in both hot and humid (less cooling energy requirements) and potentially cooler (heating required) parts of Sri Lanka. Also, its breathability helps properly regulate the indoor humidity, makes the indoor environment healthier, and may help reduce the chances of Mold growth in humid climates. It is also lightweight, making transportation easier and lighter requirements of the structure. The performance limitations are low structural strength (cannot be load bearing), is affected when exposed to water unless in protected conditions, and requires mixing and applying abilities. This feasibility relies on the installment of regulatory hurdles as industrial hemp is cultivated in Sri Lanka (though it is not worldwide, because of its association with cannabis, it has regulatory hurdles globally. However, there are varieties with less THC) or the possibility to form import channels of hemp hurds. Local availability and the cost of suitable lime binders are also important considerations.

Fig 2: Hempcrete

3.1.3 Recycled Aluminium and Steel

One of the most mature and impactful strategies to reduce the environmental burden of the materials sector is the recycling of metals such as aluminum and steel. Both materials are highly recyclable without significant loss of properties and are ideal for a circular economy.

Instead of producing aluminum from raw aluminum ore by using a highly energy-intensive smelting process (ex., bauxite ore), the primary environmental benefit of recycling aluminum is that it saves up to 95% of the energy needed than the primary aluminum production. Similarly, recycling steel uses 70 percent less energy than producing steel using ferroscopic in a blast furnace [5]. Recycling reduces the demand for virgin raw materials, thus mitigating the environmental adverse effects of resource mining, such as land degradation, destruction of habitats, and water pollution.

It saves on air and water emissions associated with primary production, and the process is far more energy efficient than past methods such as plasticulture.

Generally speaking, the performance can often replace virgin material in many cases, mainly when the sorting (or control of contamination) and alloying (reintroducing necessary alloy elements) of recycled material are carefully managed. In this context, local scrap collection, sorting, processing efficiency, and scale are significant challenges [11]. Formalizing and scaling these operations, assuring quality control for use in downstream operations, and creating local small-scale mills for steel or aluminum foundries are all necessary for maximizing domestic environmental benefits.

Fig 3: Recycled Aluminium and Steel

3.1.4 Bamboo and Engineered Wood

More and more bamboo and engineered wood products are considered viable options for standard timber or carbon-intensive materials. Bamboo is a rapidly renewable grass that grows fast, with the maturity period being only 3 to 5 years instead of decades for most timber species. Characteristic of high tensile strength, it can be used in structural and non-structural applications after proper treatment.

By binding small pieces together and using engineered wood products such as Glued Laminated Timber (Glulam), Cross Laminated Timber (CLT), or Laminated Vener Lumber (LVL), the use of timber is optimized to get the most out of timber. Both can use fast-growing or less conventionally used timber species and the parts of the log that would otherwise go to waste. During growth, both materials sequester carbon. However, this depends partly on sustainable forestry/bamboo cultivation practices and energy in the processing. For Lesser Embodied Energy and Carbon Footprint, they are usually compared to concrete and steel, except for cases with minimal long-distance transport.

Fig 4: Bamboo and Engineered Wood

There are challenges with the performance of bamboo in Sri Lanka's tropical climate: if not treated, bamboo is vulnerable to fungal decay or insect attack. Standardizing bamboo products and building codes that consider bamboo a modern structural material is also needed. Sourcing timber for engineered wood is both farmed and requires careful management of Sri Lanka's Forest resources and possibly certified imports. Engaged wood has local processing facilities, but generally imports finished products. The opportunity to promote bamboo cultivation on degraded land or non-forest areas, combined with local processing innovation, could be realized in Sri Lanka.

3.1.5 Bioplastics and Biodegradable Polymers

Bioplastics are created from corn starch, sugarcane, or algae and can either be biodegradable or contain natural material. Examples include PLA, PHAs, and blends of starch materials. These items are eco-friendly as they use less oil and offer a chance to lessen the large amounts of plastic waste that does not break down. Nonetheless, these pros vary with the feedstock, the energy needed to produce it, and what happens to it after use.

PLA, made from corn or sugarcane, has a smaller carbon footprint than usual plastics and only composts in industrial facilities, which we currently lack in Sri Lanka. PHAs are produced by bacteria through fermentation, but they are found in oceans and are pricey, with few uses. Most bioplastics do not work as well for long-term use as petroleum-based plastics, so they are mainly used for packaging and other consumer goods.

In the country, certain things are preventing the adoption of new technologies. There is no industrial composting system in place, there is a risk of dirt in plastic recycling, and things are much more expensive. Besides, few people understand bioplastics, and the current garbage management system cannot handle them properly. Any difficulty separating bioplastics from standard plastics might result in them being buried in landfills instead of recycled.

3.2 Environmental Impact Comparison

Life Cycle Assessment (LCA) data shows sustainable materials can significantly reduce energy use, carbon emissions, and waste. The overall trend is clear, but the impacts vary based on factors like raw materials and transport. Table 01 compares average values, though Sri Lanka-specific conditions should also be considered.

Table 01: Comparison of the materials with each other on environmental performance

Material	Primary Resource	Embodied Energy (GJ/ton)	Carbon Footprint (kg CO_2e/ton)	Water Usage (m^3/ton)	Recyclability Potential	Decomposition Time
Conventional Materials						
Ordinary Portland Cement	Non-renewable	4-6	800-1000	1.5-2	Very Low	N/A
Concrete (typical mix)	Non-renewable	1-2	150-250	0.1-0.2	Moderate (as aggregate)	N/A
Virgin Steel	Non-renewable	20-35	1500-2500	3-5	High	N/A
Recycled Steel (Electric Arc Furnace)	Recycled	5-10	400-600	1-2	High	N/A
Virgin Aluminum	Non-renewable	150-220	12000-20000	5-10	Very High	N/A
Recycled Aluminum	Recycled	6-10	400-800	0.2-0.5	Very High	N/A
Virgin Plastic (HDPE)	Non-renewable	70-80	1500-2000	0.1-0.3	Moderate	Centuries
Sustainable Alternatives						
Geopolymer Concrete	Waste/Natural	1-2	80-400	0.1-0.3	Moderate (as aggregate)	N/A
Hempcrete	Renewable	0.5-1	-500 to -100*	0.1-0.2	Low/Compostable**	N/A
Bamboo (Treated)	Renewable	0.5-1.5	-500 to 0*	0.2-0.5	High (if clean)	Years
Engineered Wood (CLT)	Renewable	2-5	-400 to 100*	0.5-1	Moderate	Years
Bioplastic (PLA)	Renewable	30-60	50-150	1-3	High (Industrial Comp.)	~90-180 days***

**Note: Negative values indicate carbon sequestration during growth, though processing can add emissions. The net value depends on the full lifecycle boundaries.*

**Note*: Hempcrete is typically compostable, but the lime binder complicates simple decomposition.

**Note*: Under specific industrial composting conditions. In landfill or natural environments, decomposition is much slower.*

3.2.1 Discussion of Comparisons

- **Energy Usage and Carbon Footprint:**

Recycled metals and geopolymer concrete are better than virgin energy and carbon footprint production. Materials based on biomass such as hemp, bamboo, and engineered wood can be carbon negative or neutral because of carbon sequestration during growth. It can, however, be countered by processing and transport emissions. Diversifying away from energy-intensive imports, such as cement clinker or virgin steel/aluminum, would also help the national energy grid and foreign exchange reserves, and using locally available resources, such as bamboo and earth blocks using low energy inputs, is very positive [13].

- **Waste Generation:**

Recycled materials, recycled aggregate in C&D waste, geopolymers in fly ash and slag, and reused metals and plastics help reduce waste by decreasing the number of waste materials in landfills. An alternative to persistent waste is biodegradable materials, and as Sri Lanka lacks space in the landfills and pollutes its environment, increasing the recycled material and safe biodegradation are important [13],[14].

- **Water Usage:**

There are differences, but not excessively: water usage depends heavily on manufacturing processes and the water scarcity in the region. However, some sustainable materials (CSEB, for example, some Bioplastics…) may be used with different water input than conventional materials. The relevance of this is more important in the watersports regions of Sri Lanka.

- **Recyclability and End-of-Life:**

Since metals can be recycled often, they are environmentally friendly and contribute to sustainable practices. Concrete made with geopolymer saves landfill space because it can be reused, and bio-based materials like bamboo or wood can be shredded or composted. As those facilities are uncommon, many bioplastics are sent to landfills instead of industrial composting in Sri Lanka. Whether a material helps the environment depends on where it is disposed of.

Using metals, geopolymer concrete, and resources such as bamboo and wood is good for the environment and helps with sustainability [21]. Many bioplastics go to landfills in Sri Lanka rather than being taken to industrial composting sites.

3.3 Contributions to Environmental Sustainability

LCA data does not accurately represent the impact of sustainable engineering material adoption on environmental sustainability goals, which are crucial for Sri Lanka's development trajectory and environmental challenges.

3.3.1 Resource Efficiency

Sustainable materials conserve resources using recycled content, reducing greenhouse gas emissions, energy consumption, and environmental impact. This is especially important in Sri Lanka, where unsustainable mining practices cause environmental degradation. Waste products serve as feedstocks, turning liabilities into valuable resources. Bamboo and sustainably managed timber plantations are renewable, continuous sources if cultivated responsibly, avoiding deforestation and biodiversity loss, a significant issue in Sri Lanka.

3.3.2 Reduced Dependency on Non-Renewables

Commonly used materials often need non-renewable resources and involve energy-intensive manufacturing. Low-temperature binders like geopolymers and lime-based renders, which are bio-based, can lower the energy requirements for making CSEBs [20]. Depending more on materials produced from renewable energy sources can benefit Sri Lanka because it reduces the country's need for imported fuels and raw materials, helping to form a stable energy policy and preserving the country's foreign exchange.

3.3.3 Circular Economy Principles

Using sustainable engineering materials is important to shift from the old take-make-dispose system to a circular economy. Examples are steel and aluminum, which can be recycled many times to create new products [27]. You can use certain types of waste, for example, industrial waste or leftover parts from agriculture, to make other products [14]. Using sustainable materials reduces the need to replace them often and encourages quick reuse when breaking down buildings. Managing biodegradable materials helps return nutrients to the soil, which completes a biological process. Organic waste management needs strong infrastructure. When these concepts are used, less waste is created, resources are used more efficiently, and the match between economic growth and the use of resources goes down. The local circular economy system requires new sorting, processing, and manufacturing equipment to handle the waste coming from the island and any potential resources [28].

3.4 Innovations and Inventions in Material Science

Material science is undergoing continuous evolution, with various material science innovations that enhance or enhance sustainability in engineering materials. On the one hand, these advancements provide new material options, while on the other hand, they enhance the performance and feasibility of existing sustainable alternatives.

3.4.1 3D-Printed Sustainable Materials

Using 3D printing (Additive Manufacturing), objects with very detailed and complicated designs can be manufactured without having to worry about extra material waste. Experts are trying to produce 3D-printable materials using geopolymers, recycled aggregates, and fibers so that we can rely less on regular formwork and nearby materials for creating structures and building components. Such technology might be economical and convenient for building housing and infrastructures in mountainous regions like Sri Lanka because less material would have to travel long distances [17],[24].

3.4.2 Smart Materials

External stimuli for innovative materials are stress, temperature, moisture, and light. To stop water from getting into the concrete through cracks, Self-Healing Concrete uses 'living' properties such as bacteria-producing calcium carbonate, enclosed polymers, and embedded systems of tubes. It benefits concrete structures by making them last longer, cutting costs, and lessening environmental adverse effects. Using thermal or mechanical shocks, Shape-Memory Alloys (SMAs) will return to their original state, making it possible to build self-centered and self-repairing steel or concrete elements with less repair needed [20]. Even though they are costly right now, SMAs could result in fewer climate effects over the lifetime of infrastructure [27].

3.4.3 Bio-fabrication and Biomimicry

In bio-fabrication, you can use biological processes or organisms, such as mycelium fungi, to grow materials for eco-friendly insulation panels. Mineral sediment from bacteria turns into natural bio cement that lowers the environmental effect. They happen at ambient temperatures, and you need little energy, as only wastes are involved. It is challenging to control biological processes regarding repeatability, expanding production, and the required strength.

It looks to imitate natural features to make new materials and products. One method is to design strong but lightweight composites by using the arrangement of bones in the body, and leading coatings can be invented using the self-cleaning technique of lotus leaves. It starts with better-looking solutions but usually ends with materials that last longer, stay strong, and have fewer adverse effects during their life span.

3.4.4 Industry 4.0 and AI in Sustainable Material Design

They can play a role in making it possible to use more sustainable materials faster. Thanks to Industry 4.0, using IoT, advanced sensors, and automation in material production, less energy is used, and waste is reduced. It is easier to oversee supply chain management with the help of digital material tracking and recycling checks. AI can analyze a significant amount of data, predict the behavior of new materials, and control manufacturing processes with less effect on the environment. AI can review LCA results to find the main issues and suggest possible solutions [28]. These improvements will determine the use of sustainable resources in the future, and more R&D facilities are required to allow industry and universities to cooperate and implement them in Sri Lanka. Even so, these technologies should be prepared and put into practice according to local resources and challenges. They are essential for the development of sustainable materials.

3.5 Challenges and Considerations

Even though sustainable engineering materials are encouraging, their use in Sri Lanka brings about several problems. The main challenge is that since sustainable products are in short supply and made in smaller amounts, they often cost businesses more initially. In the long run, lifecycle costing is beneficial, yet capital expenditure is a big problem for developing economies such as Sri Lanka. Both the supply of raw materials and the industrial procedures must be adequate to produce materials that are considered sustainable. Fulfilling the country's needs calls for a significant boost in investment, for example, making large-scale processing plants and recycling different plastics streams.

Because building codes and standards for sustainable materials are missing in Sri Lanka, it is a big obstacle [29]. Old rules in the building industry stress using traditional properties and familiar materials, so it is hard for engineers and architects to use bamboo or CSEB in their projects. Financial regulators and research institutes are developing and applying new financial regulations, although the updates are not quick to be introduced. Stakeholders oppose change daily, concerned about unfamiliarity, possible dangers, and existing bonds with traditional suppliers. Pilot studies are important because they can address the resistance. However, it is not easy to gain confidence unless awareness and education campaigns are carried out at every level of the construction sector in Sri Lanka. People's taste in culture and style affects the use of sustainable materials.

People in Sri Lanka have little knowledge and practical ability to use sustainable materials for design and construction. One can observe this in the University's engineering and architecture courses since these topics could be excluded [17]. Construction workers should know how to work well with materials such as treated bamboo, CSEB, and prefabricated bio-composite panels. Good supply chains that source nearby sustainable products are essential and should stay accessible, reliable, and quality. This affects farmers, involves communities, suggests better ways to harvest and process produce, and ensures quality is always intact. Enhancing transportation on the island could reduce negatives to the environment and money.

Information about the carbon footprint of sustainable materials in Sri Lanka is mostly not detailed or correct, and databases abroad may be wrong since they do not consider local energy systems, travel distances, or how industries work. Findings will help Sri Lanka make better decisions when detailed research is done on important materials. Because Sri Lanka has high temperatures and much rain, along with solar radiation and termites, building in the country is difficult for materials. Since bamboo is easily attacked, special care and research should be given to using eco-friendly insect and fungal treatments in local areas. These challenges can be solved by relying on technology and policies, making the needed investments, remodeling schools, uniting industries, and involving the public.

3.6 Global Adoption Trends

This movement towards green materials is growing in an orderly and accelerating manner globally, where the forces for using green materials are amplified by growing environmental awareness and government legislation, rapid demand for green buildings, and technology for green materials. The views of global trends prove to be practical and even possible road maps for countries such as Sri Lanka.

3.6.1 Countries Leading in Green Materials

You can find many nations and areas embracing sustainable materials, and Scandinavian and Western European countries have plenty of experience there. Sweden, Norway, Finland, and Germany are among the Scandinavian countries with strong rules promoting a circular economy, making buildings energy efficient, and approving sustainable materials. Countries that have timber in their forest resources and apply sustainable forest care use timber. Green building is a main priority for China, which makes and uses fly ash geopolymers in large quantities. Many areas in Africa, Australia, and South America where earth building is old are now checking out CSEB techniques [27]. The governments of these nations make it easy for businesses to be green, research and innovation to thrive, waste can be recycled in developed facilities, and the public cares a lot.

3.6.2 Examples of Infrastructure Projects Using Sustainable Materials

Here are just some of the viable and benefit high profile projects around the world:

- **Wooden Skyscrapers:**
  The world's tallest wooden building is the Mjøstårnet in Norway (85m tall), and HoHo Wien in Austria (84m tall) use large amounts of CLT and Glulam as the primary structure material and provide strong evidence that GL and CLT can be used extensively in high buildings and with less embodied carbon than steel and concrete equivalents.
- **Bridges and Infrastructure:**
  High-performance concrete projects combining relatively large amounts of slag or fly ash (geopolymers or blended cement) are becoming commonplace to reduce carbon footprint in projects worldwide. In a few progressive projects, fiber-reinforced polymer (FRP) composites made from remade plastics or biocomposites have possibly a place with non-significant structural components or bridge decks.
- **Stadiums and Large Span Structures:**
  For specific spans, however, the strength, aesthetics, and lower environmental impact of engineered timber compared to conventional steel structures for the stadium and large public building roofs and structural elements is being used increasingly.
- **Affordable Housing Initiatives:**
  In many areas of Asia and Africa, initiatives are being made to introduce CSEB, bamboo, and other locally available materials of low carbon level to promote sustainable and affordable housing.

These case studies provide key examples of how sustainable materials can be used in high-performance, wide array of critical and large-scale infrastructure requirements. They help the engineers, developers, and the masses build confidence.

3.6.3 Market Growth

Green building materials have gained momentum in the global market. Many green building certification programs (such as LEED and BREEAM) demand green building materials, government regulations, and corporate sustainability commitments. This growth provides opportunities for businesses to produce, supply, and construct with these materials. That means this is a maturing market, and availability is increasing, which may result in cost reduction as an economy of scale is reached.

3.6.4 International Standards and Certifications

They play a significant role in the development and harmonization of international standards (for example, the series ISO 14000 on environmental management and ISO 21930 for sustainability in building construction) and in spreading green building rating systems (LEED, BREEAM, Green Star, and others) [29]. They apply common languages to materials and buildings, such as environmental performance, and create market incentives for sustainable options. Sri Lanka has taken some initiatives in green building ratings, e.g., the GreenSL® Rating System. However, this needs to be complemented with a more substantial alignment of national standards and certifications to international good practices on sustainable materials and practices.

3.6.5 Relevance and Lessons for Sri Lanka

Sri Lanka can draw valuable lessons from global adoption trends.

- **Policy is Key:**
  Elsewhere, supportive government policies, incentives, and more recent regulations also played a crucial role. This has to be a priority for Sri Lanka.
- **Leverage Local Resources:**
  Local resources abound (timber in Scandinavia, earth in other areas), and the countries effectively use them. Bamboo, agricultural waste, and specific mineral resources in Sri Lanka are unique. Optimization of these should be the focal point of R&D.
- **Pilot Projects Build Confidence:**
  Showing local examples of these projects' success and feasibility is crucial in the Sri Lankan context.
- **Capacity Building is Essential:**
  Developing local expertise for designing, constructing, and maintaining requires investing in education and training.
- **Align with Global Standards:**
  By harmonizing local standards with international ones, sustainable material provenances become easier to adopt and attract investment.
- **Circular Economy Focus:**
  Learning from countries with advanced recycling and waste-to-resource systems is essential in improving Sri Lanka's waste management and integrating recycled content into the material.

Sri Lanka should choose sustainable engineering materials globally, using local resources, offering more jobs, and helping the country endure climate challenges. Simply put, the engineering sector backs people moving to these products because they aim to help the environment [30]. Then, to use the island successfully, one should understand island costs, rules and regulations, the flow of products, and the island's capacity, along with its strengths in global markets.

4. CONCLUSION

It looks at the possible upsides and downsides of using Compressed Stabilized Earth Blocks (CSEBs), bamboo, and recycled aggregates for construction in Sri Lanka. According to the research, these sustainable materials might revolutionize the industry by keeping up with global and local sustainability requirements. When mixed with stabilizers such as cement or lime, soil-based bricks are environmentally friendly since they use less energy and produce less greenhouse gas. Since bamboo is very easy to grow, it was effectively used in projects like the UNA eco-hotel [15]. These aggregates are taken from waste construction and demolition materials, which helps decrease the use of landfills and protects valuable resources [13].

Sri Lanka uses sustainable materials harmoniously with the United Nations Sustainable Development Goals (SDGs), mainly SDG 11 and SDG 13. Using this strategy results in less energy-consuming materials, which, in turn, cuts the construction sector's carbon emissions. It helps rural communities, offers jobs to people, and maintains age-old ways of constructing buildings. However, people face problems due to a lack of information, not knowing the technology well, and regulations already implemented. The cost of choosing sustainable materials can be greater initially, so it is harder for them to be used by many organizations that would later see significant savings.

Actions such as creating tax breaks, handing out grants, and carrying out sustainability checks should be taken by the government [26]. Efforts should be made to create training classes for architects, engineers, and contractors; the Industrial Development Board can play a significant role. Studies should take place to make sustainable materials more suitable economically and in terms of their performance. Collaborations between academic institutions and businesses may bring about innovation and knowledge sharing. Teaching people about sustainable construction can cause more people to want to support and use green buildings. Using media, holding seminars, and organizing demonstration projects are helpful, too. Creating standards and providing certificates for sustainable materials can guarantee their excellent quality and help professionals and customers trust them.

REFERENCES

[1] J. M. Allwood, J. M. Cullen, and R. L. Milford, "Options for achieving a 50 % cut in industrial carbon emissions by 2050," *Environ. Sci. Technol.*, vol. 44, no. 6, pp. 1888–1894, 2012, doi: 10.1021/es902909k.

[2] American Chemical Society, "12 Principles of Green Engineering," *American Chemical Society*. [Online]. Available: http://www.acs.org/.../12-principles-of-green-engineering.html. [Accessed: Apr. 12, 2025].

[3] M. F. Ashby, *Materials and the Environment: Eco-Informed Material Choice*, 2nd ed. Oxford, UK: Butterworth-Heinemann, 2013.

[4] N. M. P. Bocken, S. W. Short, P. Rana, and S. Evans, "A literature and practice review to develop sustainable business model archetypes," *J. Clean. Prod.*, vol. 65, pp. 42–56, 2014, doi: 10.1016/j.jclepro.2013.11.039.

[5] T. L. Chen *et al*., "Implementation of green chemistry principles in circular economy system towards sustainable development goals: Challenges and perspectives," *Sci. Total Environ.*, vol. 716, p. 136998, 2020, doi: 10.1016/j.scitotenv.2020.136998.

[6] Constructive Voices, "Sri Lanka Top Green Buildings," 13 Feb. 2024. [Online]. Available: https://constructive-voices.com/sri-lanka-top-green-buildings/. [Accessed: Apr. 12, 2025].

[7] G. Habert, D. Arribe, M. Dehestani, and S. Lasvaux, "Reducing environmental impact through green concrete: From strategy to implementation," *Cement Concr. Res.*, vol. 132, p. 106038, 2020, doi: 10.1016/j.cemconres.2020.106038.

[8] G. P. Hammond and C. I. Jones, *Inventory of Carbon and Energy*, Bath, UK: University of Bath, 2006.

[9] International Energy Agency, *Cement*, IEA, 2023.

[10] W. G. P. L. K. Jayasena *et al*., "Assessing the Key Construction Safety Challenges in Sri Lanka: A Survey-Based Study," *Infrastructures*, vol. 9, no. 1, art. 2, 2024. [Online]. Available: https://www.mdpi.com/2313-576X/11/1/2. [Accessed: Apr. 12, 2025].

[11] A. Jayasinghe, R. Rameezdeen, T. Ramachandra, and A. Rodrigo, "Enablers for facilitating life cycle assessment: key stakeholder perspectives of Sri Lankan construction industry," *Built Environ. Proj. Asset Manag.*, vol. 12, no. 5, pp. 812–827, 2022, doi: 10.1108/BEPAM-07-2021-0129.

[12] S. V. Joshi, L. T. Drzal, A. K. Mohanty, and S. Arora, "Are natural fiber composites environmentally superior to glass fiber reinforced composites?," *Compos. Part A Appl. Sci. Manuf.*, vol. 35, no. 3, pp. 371–376, 2004, doi: 10.1016/j.compositesa.2003.09.016.

[13] G. Karunasena, U. Rathnasiri, and S. Senaratne, "Investigation of the challenges of executing sustainable construction practices in the Sri Lankan construction industry," in *11th World Constr. Symp.*, 2016, pp. 625–636.

[14] M. Lawrence, "Reducing the Environmental Impact of Construction by Using Renewable Materials," *J. Renew. Mater.*, vol. 3, no. 3, pp. 163–174, 2015, doi: 10.7569/JRM.2014.634112.

[15] F. J. Lozano *et al*., "New perspectives for green and sustainable chemistry and engineering...," *J. Clean. Prod.*, vol. 172, pp. 227–232, 2018, doi: 10.1016/j.jclepro.2017.10.190.

[16] M. Malkanthi, "Compressed Stabilized Earth Blocks with Construction Waste and Coconut Fiber," *The Institution of Engineers, Sri Lanka*, 2021. [Online]. Available: https://iesl.lk/SLEN/61/Compressed_Stabilized_Earth_Blocks.php. [Accessed: Apr. 27, 2025].

[17] K. W. Meereboer, M. Misra, and A. K. Mohanty, "Review of recent advances on biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their green composites," *Green Chem.*, vol. 22, no. 17, pp. 5519–5558, 2020, doi: 10.1039/D0GC02159K.

[18] G. T. Miller and S. E. Spoolman, *Living in the Environment*, 19th ed. Boston, MA: Cengage Learning, 2018.

[19] Ministry of Urban Development and Housing, Sri Lanka, *Sri Lanka Sustainable Housing and Construction Roadmap 2020–2050*. [Online]. Available: https://moudh.gov.lk/... [Accessed: Apr. 12, 2025].

[20] A. K. Mohanty, M. Misra, and L. T. Drzal, "Sustainable bio-composites from renewable resources: Opportunities and challenges...," *J. Polym. Environ.*, vol. 10, no. 1, pp. 19–26, 2002, doi: 10.1023/A:1020350230512.

[21] G. T. Miller and S. E. Spoolman, *Living in the Environment*, 19th ed. Boston, MA, USA: Cengage Learning, 2018.

[22] Ministry of Urban Development and Housing, Sri Lanka, *Sri Lanka Sustainable Housing and Construction Roadmap 2020–2050*. [Online]. Available: https://moudh.gov.lk/... [Accessed: Apr. 12, 2025].

[23] A. K. Mohanty, M. Misra, and L. T. Drzal, "Sustainable bio-composites from renewable resources: Opportunities and challenges in the green materials world," *J. Polym. Environ.*, vol. 10, no. 1, pp. 19–26, 2002, doi: 10.1023/A:1020350230512.

[24] A. K. Mohanty, S. Vivekanandhan, J. M. Pin, and M. Misra, "Composites from renewable and sustainable resources: Challenges and innovations," *Science*, vol. 362, no. 6414, pp. 536–542, 2018, doi: 10.1126/science.aat9071.

[25] S. M. A. Nanayakkara, *Towards a Sustainable Building Stock in Sri Lanka*, IESL SLEN, 2021.

[26] J. A. Ochsendorf, “Sustainable Engineering: The Future of Structural Design,” in *Struct. Congr. 2005*, New York, NY, USA, 2005, pp. 1–9, doi: 10.1061/40754(178)1.

[27] H. P. S. H. Perera *et al*., “Assessing benefits of developing a simulation model for sustainable constructions using Life Cycle Assessment (LCA) Approach in Sri Lanka,” in *Proc. 16th Int. Res. Conf. Gen. Sir John Kotelawala Defence Univ.*, Sri Lanka, 2023. [Online]. Available: http://ir.kdu.ac.lk/... [Accessed: Apr. 12, 2025].

[28] J. Płotka-Wasylka *et al*., “Green Chemistry in Higher Education: State of the Art, Challenges, and Future Trends,” *ChemSusChem*, vol. 11, no. 17, pp. 2845–2858, 2018, doi: 10.1002/cssc.201801070.

[29] M. A. Rosen, “Engineering Sustainability: A Technical Approach to Sustainability,” *Sustainability*, vol. 4, no. 9, pp. 2270–2292, 2012, doi: 10.3390/su4092270.

[30] K. Seneviratne, C. Jayasinghe, and R. Rameezdeen, “Exploring Traditional Building Materials for Urban Housing in Sri Lanka,” in *Proc. 6th Int. Conf. Res. Transp. Logist. Industry & 16th Int. Res. Conf. Manag. Finance*, Univ. of Sri Jayewardenepura, Sri Lanka, 2024, pp. 165–176.