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Build for Tomorrow: Sustainable Materials for Smarter Cities

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Abstract

Sustainable materials are revolutionizing urban development by reducing the carbon footprint of buildings, fostering climate-smart and resilient cities. Key examples include green concrete, which utilizes industrial waste and lowers greenhouse gas emissions, and recycled steel, which requires less energy than producing new steel. Cross-laminated timber (CLT) is also gaining popularity for its strength and renewability, offering a sustainable alternative to traditional building materials. Smart glass, which adjusts light transmission, based on external conditions, and phase change materials, which absorb and release thermal energy, enhance building efficiency by optimizing indoor climate. Additionally, organic photovoltaics (OPVs) represent a groundbreaking approach to solar energy, featuring flexibility and lightweight characteristics ideal for diverse building applications. Green roofing, which involves rooftop vegetation, improves insulation, supports urban biodiversity, and reduces stormwater runoff. Permeable pavements further reduce flooding risks by allowing water infiltration, while recycled plastics are repurposed into construction materials to minimize waste and conserve resources. The ultimate aim of smart cities is to create resilient, sustainable, and efficient urban environments that prioritize both technological advancement and human well-being. This study explores the extensive literature on sustainable materials and their effective use in various building components. By integrating net-zero practices and sustainable materials, architects and engineers can create buildings that are not only energy-efficient but also contribute positively to the environment, leading the way in green urban development.

Keywords: Smart city, sustainable building materials, green materials, net zero buildings, green construction matrix

INTRODUCTION

According to the World Bank Urban Development webpage, with rapid urbanization sweeping across the globe, cities are facing an ever-growing demand for resources and infrastructure. Creating smarter cities now involves more than just technology integration; it also requires a focus on sustainability, resilience, and responsible resource management. Sustainable materials, engineered to reduce environmental impact, minimize waste, and increase durability, are becoming essential components of modern urban planning and construction. From renewable resources like bamboo to recycled concrete and advanced energy-efficient materials, the adoption of sustainable materials is a critical step toward building smarter, more resilient cities that can thrive while lowering their ecological footprint [1].

A Positive Energy District (PED) is an urban area or neighborhood designed to generate more energy than it consumes, enhancing both sustainability and self-sufficiency [2]. PEDs combine renewable energy sources, energy-efficient buildings, smart

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grids, and energy storage systems to work in synergy, reducing energy waste and lowering the environmental impact of the community.

By integrating net-zero practices and sustainable materials, architects and engineers can create buildings that are not only energy-efficient but also contribute positively to the environment, leading the way in green urban development [3].

KEY GREEN MATERIALS FOR SMARTER CITIES

Some of the key sustainable materials/technologies used to craft smarter cities are green concrete, recycled steel, bamboo, mycelium, cross laminated timber, solar panels, cool roofing materials, permeable pavements, recycled plastics, sustainable insulation, smart glass, geopolymer cement, organic photovoltaics, phase change materials and biodegradation [4]. Let us take a closer look at them.

Green Concrete

- Incorporates industrial byproducts such as fly ash, silica fume, and slag.
- Offers a lower carbon footprint than conventional concrete.
- Is suitable for construction of buildings, roads, and other infrastructure projects.

Recycled Steel

- Is extremely durable and fully recyclable.
- Minimizes the demand for new raw materials.
- Is commonly used in infrastructure projects.

Bamboo

- Is rapidly renewable and fast-growing.
- Offers a high strength-to-weight ratio.
- Is ideal for use in flooring, furniture, and even structural components.

Mycelium

- Is the root structure of fungi, can be grown into strong, lightweight, and fire-resistant building blocks.
- Is excellent for use in insulation, wall panels, and temporary structures.
- Is fully compostable, and so naturally breaks down at the end of their life cycle, making it an eco-friendly choice for sustainable construction.

Cross-Laminated Timber (CLT)

- Is a strong yet lightweight engineered wood material.
- Is carbon-neutral and capable of storing carbon dioxide.
- Is commonly used in high-rise buildings and various other structures.

Solar Panel

- Harnesses sunlight to generate electricity, decreasing dependence on fossil fuels.
- Can be integrated into building designs, rooftops, and facades.

Cool Roofing Material

- Reflects a greater amount of sunlight and absorbs less heat.
- Helps mitigate the urban heat island effect and reduce energy consumption for cooling.

Permeable Pavement

- Facilitates water infiltration, helping to reduce runoff and replenish groundwater.
- Is constructed from materials such as porous asphalt, pervious concrete, and interlocking pavers.

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Recycled Plastic

- Is used in construction materials such as bricks, lumber, and insulation.
- Decreases plastic waste and minimizes landfill use.

Sustainable Insulation

- Is composed of materials such as sheep's wool, cellulose, and recycled denim.
- Offers efficient thermal regulation while remaining environmentally friendly.

Smart Glass

- Modifies its tint according to sunlight levels, thus minimizing the requirement for artificial lighting and air conditioning.
- Boosts energy efficiency in buildings.

Geopolymer Cement

- Composed of industrial byproducts such as fly ash and slag.
- Produces reduced carbon emissions in comparison to conventional Portland cement.

Organic Photovoltaics (OPVs)

- Constructed from organic materials and utilized in flexible solar panels.
- Offers potential for integration into a variety of surfaces, such as windows and walls.

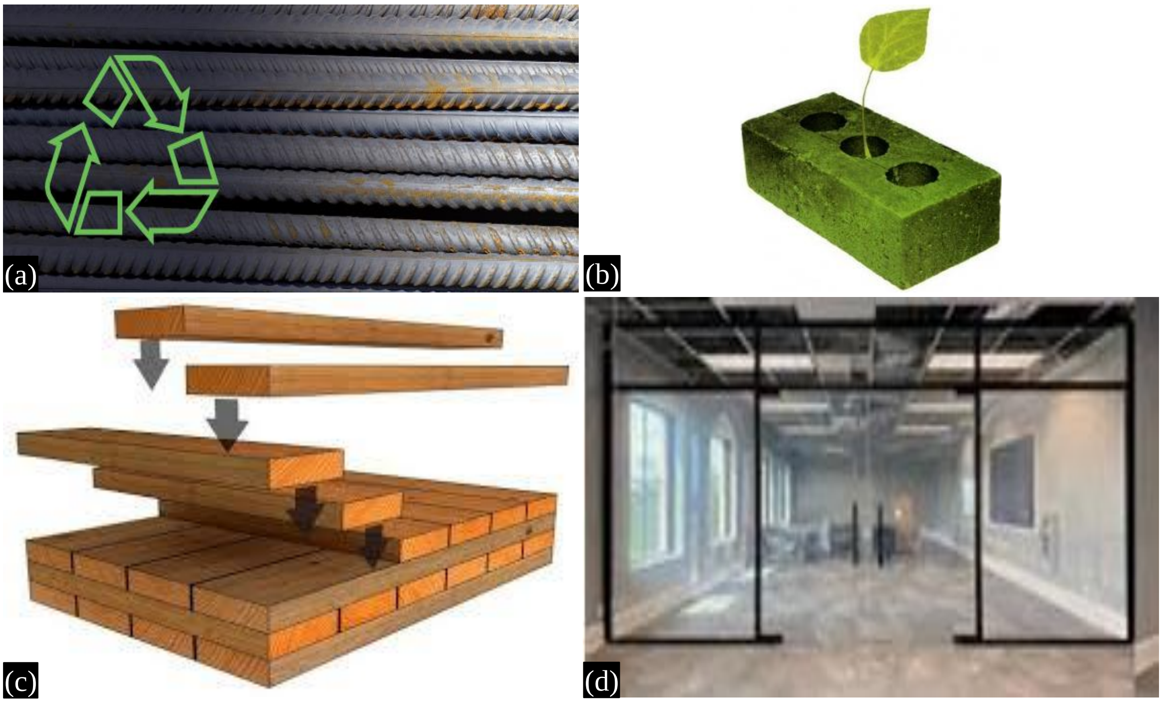
Phase Change Material (PCM)

- Stores and releases thermal energy during phase changes.
- Incorporates into building materials to enhance energy efficiency and thermal comfort.

Biodegradation

- Is a process in which bacteria break down organic matter in wastewater, helping to reduce pollutants and improve water quality.

Figure 1 shows some of the different sustainable materials.



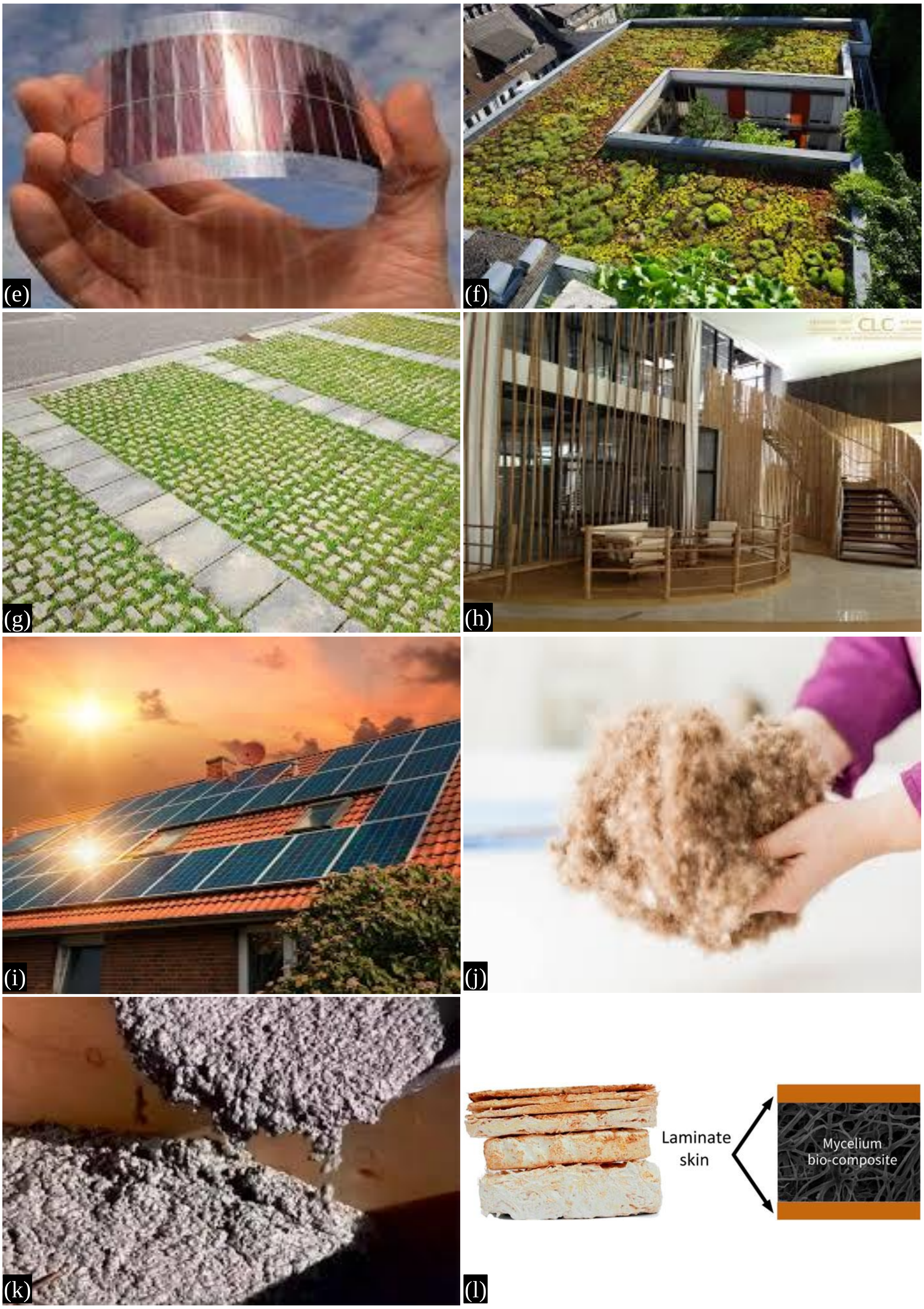


Figure 1. Different sustainable materials. (a) recycled steel, (b) green concrete, (c) cross laminated timber (CLT), (d) smart glass, (e) organic photovoltaics (OPV), (f) green roof, (g) permeable pavement, (h) bamboo, (i) solar panels, (j) sustainable insulation, (k) geopolymer concrete, (l) mycelium biomaterial.

INTRODUCTION TO SUSTAINABLE SMART CITIES

In the modern urban landscape, cities are increasingly expanding vertically, which has led to the widespread phenomenon known as the urban heat island effect [5]. This effect, characterized by elevated temperatures in urban areas compared to their rural surroundings, is primarily driven by the extensive use of concrete and asphalt, which absorb and retain heat. As cities continue to grow into concrete jungles, the need for innovative solutions to mitigate heat dissipation becomes critical. One of the solutions is to coat roads and roofs with white reflective paint and plant more vegetation. Smart cities in India are being designed with a focus on sustainability and human-centric development. However, the challenge remains that not all construction materials used are environmentally friendly, potentially undermining the goals of creating climate-resilient urban spaces.

To address this issue, this study proposes a comprehensive matrix for evaluating sustainable building materials tailored to different components of smart city infrastructure. By categorizing materials based on their environmental impact, durability, and suitability for specific building elements, planners and architects can make informed decisions that prioritize sustainability. Additionally, landscaping materials play a vital role in enhancing urban aesthetics and functionality, contributing to effective heat management and biodiversity. Incorporating green roofs, permeable pavements, and native plant species can significantly improve urban microclimates and reduce the overall heat footprint of cities. According to UNECE Sustainable Development Goals, by integrating sustainable materials across all aspects of urban development, smart cities can foster environments that are not only livable but also resilient to climate change [6].

REVIEW OF LITERATURE

Table 1 shows the CO_2 emitted in different constructions. A particular paper by Tazmeen and Mir has been referred to for the literature reviewed here [7]. Hong *et al*. studied the behavior of reinforced concrete structures, focusing on improving the structural performance and durability through innovative reinforcement techniques and materials [8]. Ezema *et al.* explored reinforced concrete frames, focusing on sustainable design practices in structural systems [9]. Williams *et al.* investigated reinforced steel concrete, emphasizing the enhancement of structural resilience and load-bearing capacity through optimized steel reinforcement and concrete composition [10]. Hacker *et al*. analyzed concrete's thermal mass properties, highlighting its potential to improve energy efficiency in buildings by reducing heating and cooling demands [11]. Mathur *et al*. studied masonry steel structures, focusing on the integration of steel reinforcement in masonry to enhance structural stability, load-bearing capacity, and seismic resistance [12]. Fu *et al.* investigated masonry-wall timber frame systems, highlighting their combined structural performance and the potential for improving energy efficiency and earthquake resistance in building construction [13]. Hacker *et al.* examined the use of timber in construction, emphasizing its sustainability and its ability to reduce carbon emissions when used as a renewable building material [11]. Ortiz *et al*. assessed the environmental impact of brick production, focusing on the life-cycle analysis and proposing strategies to reduce energy consumption and emissions in brick manufacturing [14].

Table 1. The CO_2 Emitted in single story simple constructions.

Construction material	Quantity of CO_2 emitted	Researcher (year)
Reinforced concrete structure	8707004 kg CO_2e	Hong *et al.* (2015) [8]
Reinforced concrete frame	2395 kg/m^2	Ezema *et al*. (2016) [9]
Reinforced steel concrete	467 kg CO_2e/m^2	Williams *et al.* (2012) [10]
Concrete	569 kg CO_2/m^2	Hacker *et al*. (2008) [11]
Masonry steel	189 kg CO_2e/m^2	Mathur *et al.* (2021) [12]
Masonry-wall timber frame wall	432 kg CO_2/m^2	Fu *et al*. (2014) [13]
Timber	492 kg CO_2/m^2	Hacker *et al*. (2008) [11]
Bricks based	246 kg CO_2e/m^2	Ortiz *et al.* (2010) [14]

DISCUSSION

Smart cities benefit from sustainable materials in construction in several key ways [15]:

1. *Reduced environmental impact:* Sustainable materials, such as recycled plastics, bamboo, and low-carbon cement, significantly lower carbon emissions and waste production. This contributes to a smaller ecological footprint for urban development and helps combat climate change.
2. *Energy efficiency:* Many sustainable materials enhance energy efficiency in buildings. For example, insulated materials can reduce heating and cooling needs, leading to lower energy consumption. This not only saves costs but also decreases reliance on fossil fuels.
3. *Improved urban resilience:* Using durable and sustainable materials can enhance the resilience of infrastructure against climate-related events, such as heavy rainfall or extreme heat. This contributes to long-term urban sustainability and safety.
4. *Enhanced livability:* Sustainable materials often contribute to healthier indoor environments by improving air quality and reducing the presence of harmful chemicals. This promotes the well-being of residents and creates more comfortable living spaces.
5. *Economic benefits:* Investing in sustainable construction materials can lead to cost savings over time through reduced energy bills and maintenance needs. Additionally, the growing demand for green building practices can create jobs and stimulate local economies.
6. *Community engagement:* Incorporating sustainable materials often involves community input and participation, fostering a sense of ownership and pride among residents. This can lead to stronger community bonds and more engaged citizenry.

By integrating sustainable materials into their construction practices, smart cities can create more efficient, resilient, and livable urban environments that are better equipped to face future challenges.

CASE STUDY: MASDAR

Basic Information

Masdar is located in Abu Dhabi, UAE, covering an area of 700 ha (7 km^2). This mixed-use city aims to accommodate approximately 40,000 residents, with an additional 50,000 commuters. Construction is ongoing, with several structures and systems already completed and operational. The city is situated in a tropical dry region characterized by high temperatures year-round and extremely hot summers typical of a desert climate.

Vision and Objectives

Masdar aspires to achieve a zero waste objective while incorporating innovative public transportation systems. The city’s design emphasizes energy-efficient technologies and smart architecture to minimize environmental impact. Additionally, Masdar will be entirely powered by renewable energy sources, aligning with its sustainability goals [16].

Smart Living

The city’s master planning draws inspiration from traditional settlement patterns and built environments, featuring narrow streets and natural shading elements. The urban design promotes high-density, low-rise living, with most buildings limited to five stories. Key planning principles include clustering the main retail district, hotels, and business areas alongside the city’s headquarters [17]. Educational institutions are strategically located near residential zones while remaining connected to the city center. The urban environment encourages outdoor interaction, creating vibrant streets and squares that foster community engagement. Elevating the site above the surrounding terrain provides a cooling effect, and a perimeter wall helps block harsh desert winds, enhancing the city’s livability.

Smart Environment

Significant environmental benefits are achieved through simple, passive design strategies. The initial focus was on optimizing building orientation and performance, which effectively reduces energy demands at minimal cost. The pedestrian-oriented layout features narrow, shaded streets and pleasant

Figure 2. Terracotta screens and trees in residential blocks.

Figure 3. Shading in residential blocks.

pathways that encourage walking. Streets typically measure no more than 70 m in length, and the building designs create wind turbulence that pushes air upward, generating a cooling effect throughout the area. As a result, temperatures in the streets are generally much cooler than those in the surrounding desert, contributing to a more comfortable urban experience. Figures 2 and 3 show local construction materials and techniques at Masdar.

IMPORTANT ARCHITECT: DR. YEANG, MALAYSIA

Dr. Ken Yeang, a Malaysian architect and ecologist, is known for his innovative approach to sustainable architecture and urban planning. His work often emphasizes the integration of ecological principles with architectural design [17]. In India, Dr. Yeang has contributed to several projects that showcase his commitment to sustainability and environmentally responsive architecture.

One notable project is the India Tower in Mumbai, conceptual sketch shown in Figure 4, which was envisioned as a green skyscraper that integrates nature within its structure. The design includes vertical gardens, green roofs, and energy-efficient systems aimed at minimizing the building's carbon footprint. Dr. Yeang's philosophy promotes the use of local materials and climate-responsive designs, making buildings more suited to their environmental context.

Another significant aspect of Dr. Yeang's work in India is his focus on urban design strategies that enhance biodiversity and reduce urban heat. He advocates for creating urban landscapes that incorporate green spaces, promote biodiversity, and improve the overall quality of life for residents. His designs often reflect a harmonious relationship between built environments and natural ecosystems, making them a model for future sustainable developments in Indian cities. Through these projects, Dr. Yeang aims to inspire a shift toward more sustainable practices in architecture and urban planning across the region. However, the project 'India Tower', Mumbai was cancelled in 2015.

MATERIAL MATRIX

The matrix of sustainable different materials for different components of the smart building is provided in Table 2.

Figure 4. India Tower, Mumbai.

Table 2. Sustainable materials for different building components.

S.N.	Building component	Sustainable materials
1.	Structural components like floor, beams, columns, etc.	Recycled concrete, recycled steel, reclaimed wood (not advisable), new natural fibers based material using nanotechnology, cork
2.	Walls esp. load bearing walls.	Fly ash bricks
3.	Non-load bearing walls	Bamboo partitions, mycelium biomaterial partitions
4.	Windows	Smart glass, OPV
5.	Doors	Fiberglass, bamboo, recycled steel
6.	Landscape elements	Bermuda grass
7.	Roof	Green roof
8.	Waste water	Systems using bacteria

NEW FRONTIERS IN RESEARCH ON NEW MATERIALS

Apart from sustainable materials, architects use smart materials in recent constructions. Some of these smart materials are self healing concrete; shape memory alloys (SMAs), aerogel, electrochromic glass, nanomaterials, etc.

Other that this, a new material is conceived by architect Michael Greene in 2021, very microscopic plant fibers just a millimetre long, laying them together and cross laminating them across each other we can customize each piece of material; using robotic forms and fabric forms to create the shape of the material, which behaves like a tree (Figure 5) [18].

Figure 5. Structure of building with biomaterial.

CONCLUSION

Sustainable materials are the key to the future with Net zero buildings coming into vogue. Smart Cities comprise smart buildings and surrounding landscapes. Materials like green roofs, reflective white paint, bamboo partitions, recycled steel, green concrete etc. must be considered for future buildings. Planting of trees on a large scale can influence the climate of the site. Smart buildings make smarter cities in addition to smart urban design.

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