3D PRINTING TECHNOLOGY AS A SUSTAINABLE SOLUTION FOR MITIGATION OF ENERGY CONSUMPTION IN THE FACE OF THE CLIMATE CRISIS

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Abstract - In the midst of an escalating climate crisis, characterized by rising temperatures, extreme weather events, and the perilous depletion of natural resources, humanity finds itself at a crucial crossroads. The imperative to address the environmental consequences of our industrial practices has never been more urgent. This paper explores the intersection of technology and environmental stewardship, focusing on the potential of 3D printing as a transformative solution to alleviate the escalating energy consumption associated with enhancing the thermal performance of its buildings.

Keywords - 3D Printing Technology, Sustainability Approaches, Energy Efficiency, Construction Industry.

I. INTRODUCTION

Sustainable development is crucial for the survival of the planet and humankind due to the increased demand for natural resources that has accelerated the devastation of the planet's ecosystems, putting human survival at risk. This has resulted in shortages worldwide and increased costs for goods and materials due to natural resource depletion. Uncertainties in global climate change may significantly affect buildings' long-term viability and thermal efficiency, making the construction industry an important player in promoting sustainability[1].

Rapid urbanization and population growth are making current building techniques outdated. Conventional construction methods have economic shortcomings and disregard waste repurposing and environmental protection, making it difficult for low-income communities to provide affordable housing[2]. Since then, energy consumption shifts from heating to cooling, as well as an increase in HVAC inefficiency and malfunction rates, are some effects of climate change on the structures. These effects can additionally impact building-related environmental problems, operational costs, and the health and thermal comfort of occupants, depending on the future conditions in the area. Since existing structures account for a large portion of the building sector's energy use and carbon footprint, building energy efficiency has been a focus of research for many years [3][4]. 3D printing technology has the potential to decrease the environmental impact of the construction industry. The 3DCP uses 20% less water than traditional buildingtechniques and is on schedule to cut the world's energy consumption by 5% by 2025. However, more needs to be done to make it more sustainable[2]. This study aims to evaluate both the impact of 3D printing on the environment as well as the thermal and energy performance of buildings constructed with this technology and their impact on the climate crisis. It also offers an in-depth overview of how 3d printing construction materials affect thermal and energy efficiency and how it can help achieve the Sustainable Development Goals (SDGs) of the United Nations.

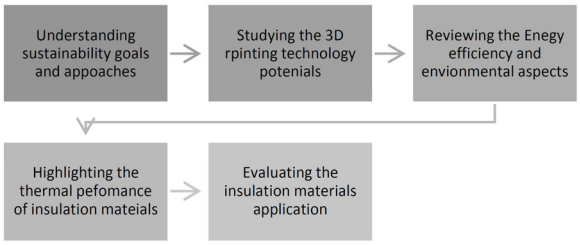


Fig. 1 The methodology adopted in the research

II. OVERVIEW OF THE SUSTAINABILITY

A. Overview of the Sustainability

Since the Industrial Revolution in the eighteenth century, mankind has focused on industrial and economic dominance in the production of products. Due to evolving technologies, processes, and materials, economic dominance has become a key factor for product development. But in the last decade, environmental issues have gained importance and it is a critical issue for current and future industries. In this context, additive manufacturing and digital technologies have allowed us to also create new environmental awareness amongst the industrial and scientific community. From the commercial perspective, economic, marketing, and social impact are key issues to be addressed. From the industrial perspective, the design, material, and processing parameters are critical aspects[5].

B. Sustainability Approaches

Sustainable development in architecture aims to reduce environmental impact, maximize resource use, and promote ecological balance. Energy and thermal

efficiency are crucial in construction to achieve these goals. Implementing green building practices, like energy efficiency, can significantly reduce energy consumption[3].3D printing creates complex designs with better material use and reduced waste, making it a sustainable option with improved energy efficiency[4].

Sustainability covers four areas: human, social, economic, and environmental, known as the four pillars of sustainability.The four pillars of sustainability must be addressed and maintained for complete sustainability. Each type of green business presents unique characteristics, so businesses need to strategically choose the approach that best fits their policies and procedures. Briefing the four pillars:

- Human sustainability: Human sustainability aims to enhance the quality of life in society through investments in health, education, access to services, nutrition, and skills development[8].
- Social sustainability: Social sustainability focuses on maintaining and improving social quality with concepts such as cohesion, reciprocity, honesty, and the importance of relationships among people. It can be encouraged and supported by laws, information, and shared ideas of equality and rights[5].
- Economic sustainability: Maintaining high and stable levels of economic growth is one of the key objectives of sustainable development. Abandoning economic growth is not an option. But sustainable development is more than just economic growth. The quality of growth matters as well as the quantity[6].
- Environmental sustainability:As described by Dunphy, Benveniste, Griffiths, and Sutton (2000), emphasizes how businesses can achieve positive economic outcomes without doing any harm, in the short- or long-term, to the environment.

C. The Sustainable Development Goals

The 17 Sustainable Development Goals (SDGs) have been adopted by the United Nations in 2015 as part of the 2030 Agenda for Sustainable Development. The 17 SDGs are to be achieved by the year 2030 and formulated as follows (cited from United Nations, 2015):

- SDG 1: No poverty
- SDG 2: Zero hunger
- SDG 3: Good health and wellbeing
- SDG 4: Quality education
- SDG 5: Gender equality
- SDG 6: Clean water and sanitation
- SDG 7: Affordable and clean energy
- SDG 8: Decent work and economic growth
- SDG 9: Industry, innovation, and infrastructure
- SDG 10: Reduced inequalities
- SDG 11: Sustainable cities and communities
- SDG 12: Responsible consumption and production
- SDG 13: Climate action
- SDG 14: Life below water
- SDG 15: Life on land
- SDG 16: Peace, justice, and strong institutions
- SDG 17: Partnerships for the goals

Additive Manufacturing (AM) can play a vital role in achieving sustainable development goals (SDGs) and their targets. Several studies have highlighted the significant potential of AM in promoting sustainable development[7].

III. 3D PRINTING OVERVIEW AND DEFINITION

3D printing, also known as additive manufacturing (AM) technology, is a process of creating solid three-dimensional structures using a computer-aided design (CAD) model. This method uses an additive process to build objects from the bottom up, by laying down successive layers of material until the object is formed. Each layer can be seen as a thinly sliced cross-section of the object [8].

A. Potentials of 3DCP in The Construction Industry

The construction industry, which relies on projects, must simultaneously meet rising demand and constrained resources. Finding the most effective solutions is getting harder as a result of pressures such as population growth, climate change, urbanization, and increasing social development demands. Innovation in construction projects is essential for project success. Noting that the development and adoption of technological and organizational innovations assisted in the construction industry's transition from a handcrafted to an industrialized business[9].

B. The Impact of 3D printing on the economy

The viability of 3D printing in construction remains uncertain in terms of cost-effectiveness. Although it can reduce labor costs, the price of 3D printable materials is often higher, and the initial expenses associated with creating a digital model are also significant. Nevertheless, a thorough cost and productivity analysis revealed that additive construction costs can be comparable to traditional methods while offering significant savings[1].

C. The Impact of 3D printing on the environment

1. Material Waste: additive construction (3D printing) results in less waste, a better carbon footprint, and reduced emissions related to transportation. It enables highly optimized construction processes and the production of highly optimized components, which naturally result in a reduction in the amount of material used[10].

2. Energy consumption:When investigating the environmental effects of manufacturing processes, the efficient use of energy is a crucial factor to consider. In the case of additive manufacturing (AM), electrical energy consumption is the most significant environmental impact. When it comes to mass production, AM consumes more electrical energy than injection molding. However, this is not the case for sample production. It's important to note that energy consumption varies depending on different parameters such as material, build volume, layer thickness, and process speed[11].
3. Air pollution:In terms of the role of AM in air pollution, two primary subdomains exist:

- Air pollution that is produced by AM processes.
- Reduction of air pollution in manufacturing using AM.

In detail, 19% of the world's greenhouse gas emissions are related to manufacturing processes[12][13]. The management of air pollution caused by various manufacturing processes is critical and requires the use of appropriate technologies. The extent of air pollution varies depending on the manufacturing processes. With the increasing use of additive manufacturing (AM) technologies in academic and industrial sectors, the impact of these technologies on air pollution has become a significant concern. Therefore, recent researches have focused on investigating the effects of desktop 3D printers on air pollution. Furthermore, the impact of AM processes on air pollution has been studied in specific cases or discussed in unique circumstances[12].

However, focusing on the impact of 3d printing technology on the environment is the main concern towards the climate crisis.

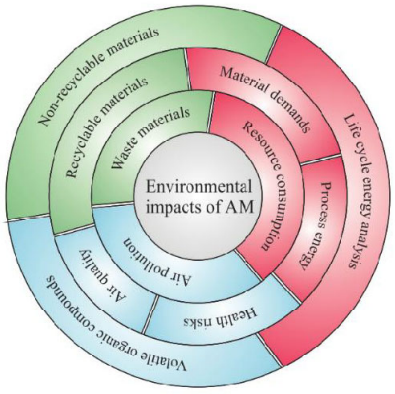


Fig. 2 Different aspects in environmental impacts of AM processes[13] (Khosravani& Reinicke, 2020)

IV. ENERGY EFFICIENCY AND THERMAL PERFORMANCE OF MATERIALS

Energy efficiency is essential for modern building design. It involves judicious material choices, cutting-edge innovations, and innovative design strategies to optimize energy consumption while reducing wasteful practices[14].Reducing energy inputs and enhancing outputs promotes sustainable and economically viable solutions. Energy efficiency is key for environmentally conscious development practices. Engineering precision and ecological mindfulness are critical for balancing long-term viability, environmental impact, and economic feasibility in building sustainable structures[15].

Thermal performance is a crucial part of energy efficiency that ensures optimal temperature regulation and heat transfer in buildings[16]. Thermal performance is crucial in architecture and construction as it promotes energy efficiency, better quality of living and working spaces, and reduces the ecological footprint of buildings.

A. Classifications of energy efficiency

Energy efficiency is crucial in construction and architecture. It involves diverse strategies to achieve its goals and includes values, classifications, and rating systems for sustainable building practices[15].

1. Passive vs Active energy efficiency: Active and passive are two classifications of energy efficiency strategies. Active strategies use innovative technology, renewable energy, HVAC, and smart systems. Passive strategies use thoughtful design and materials to reduce energy demands for construction[17].
2. Prominent rating systems:The Leadership in Energy and Environmental Design (LEED) rating system is a significant tool used in the construction industry to determine the environmental performance of sites. It was developed by the Green Building Council of the United States and covers aspects such as indoor environmental quality, water conservation, sustainable materials, and energy efficiency[5].LEED certification sets a benchmark for sustainable development practices and promotes ecologically responsible construction approaches. Other rating systems like BREEAM and Green Star also contribute to improving and assessing energy efficiency[18].

B. Thermal quality as a part of energy efficiency

Within the comprehensive terrain of energy efficiency, the responsibility of thermal quality emerges as a keystone that is woven into the perspective of sustainable building practices. Thermal quality which is a multifaceted and dynamic perspective encapsulates the holistic strategy of developing environments that are comfortable, environmentally responsible, and energy-efficient[19].

1) Fenestration and insulation design:Insulation is important for improving thermal quality. It acts as a thermal barrier to reduce heat transfer between

exterior and interior spaces. Fenestration design is also significant[20].Strategic placement of doors and windows affects the aesthetics, natural lighting, and heat loss/gain in a building. Fenestration, i.e., skylights, doors, and windows, impacts natural light and temperature. Properly designed fenestration enhances the overall atmosphere of a building and provides openings for air and water[21]. Fenestration can help with natural lighting, passive solar cooling and heating, ventilation, fire exits, and air circulation. It can also save money by reducing air leakage, improving air conditioner and furnace performance, and enhancing window thermal performance[22].

2) Choice of Building Materials:The choice of materials used in construction significantly impacts the thermal quality of a structure. Materials with high thermal mass can stabilize temperature by slowly releasing and absorbing heat, while those with insulating properties reduce heat transfer, minimizing reliance on cooling or heating systems. The strategic use of such materials is crucial for developing thermal quality in construction[23].

C. The Effect of Thermal Performance of materials on the Indoor environmental quality (IEQ)

Effective thermal performance leads to minimized energy consumption for cooling and heating purposes, reducing the need for mechanical interventions and resulting in energy conservation and a smaller carbon footprint in line with global climate goals[24]. Reducing energy consumption through improved thermal performance can have positive environmental impacts, such as reducing greenhouse gas emissions and lessening the burden on natural resources. Sustainable thermal efficiency can lead to long-term energy savings and support eco-friendly societies. Case studies can provide examples of how thermal design can benefit the environment[25][26].

V. ELIGIBLE MATERIALS FOR 3D PRINTING TECHNOLOGY IN BUILDING SKINS

The reaching of 3D printing innovation has made a new era in construction that expands the horizons of materials expectations for skins of buildingthe diverse properties of materials appropriate for 3D printing postulate builders and architects unparalleled innovation and flexibility in their pursuit of energy-efficient and sustainable structures [27].

- Concrete Blends: The flexibility of 3D printed concrete allows for optimized structural performance as well as intricate geometries that open avenues for efficient and create design of building [28].
- Polymers: Polymers are ideal for 3D printing of building skins due to their ability to be solidified and melted repeatedly, allowing for layer-by-layer deposition[29].
- Composite Materials: Composite materials in 3D printed building skins provide both aesthetic and performance solutions, as they allow for the synergism of diverse materials such as fiber, metals, or ceramics that impact structural and thermal attributes[28].

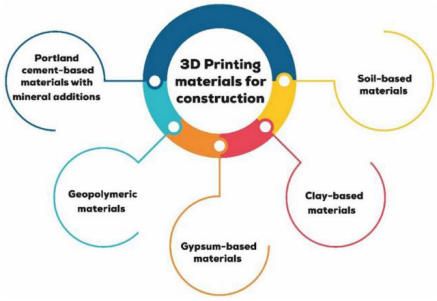


Fig. 3 Different 3D Pintable materials

A. Thermal performance of 3D Printed materials for building skins

The skin of any construction building is mentioned as the first line of defense against the external components that hold great significance in dictating thermal performance. Materials used in the building skins lead to the overall thermal effectiveness of a structure that impacts both active and passive cooling and heating approaches and plays a huge role in achieving energy efficiency for climate-enhancing seeking [30], categorizing these materials into the following:

1. Insulation Materials: Insulation materials like cellulose, foam board, and fiberglass are essential for improving thermal performance. They resist heat transfer, stabilize interior spaces, and reduce reliance on energy-efficient climate systems. The crucial trait of insulation material is its performance, which should meet manufacturer expectations. Other factors like ease of installation, protection against moisture, shrinkage, settlement, and compaction should also be considered during the design procedure[15].
2. Reflective Coatings: Reflective coatings used on roofing materials can reduce the absorption of heat, minimizing the cooling load on buildings. This approach is a testament to the role of material selection in managing thermal stress[6]. Using reflective coatings is an effective way to reduce the impact of solar radiation in both summer and winter.
3. Phase Change Materials: Phase Change Materials store and release heat during a phase change, making them a crucial solution for thermal regulations in building skins. This leads to a sustainable indoor atmosphere[31].

B. Thermal performance measurements

Thermal performance evaluation is crucial in architectural engineering for developing energy-efficient structures that offer optimal occupant comfort. Mentioning the measurement criteria:

- **Thermal Conductivity:** It refers to the ability of a material to conduct heat. In 3D printing, an understanding of the thermal conductivity of manufactured materials is essential to assess the efficiency of heat transfer[20].

- **Thermal Mass:** The heating rate plays an important role in room temperature control, especially in passive design strategies [21].

- **Solar Reflectance and absorption:**The ability to transform sunlight and absorb sunlight affect a material's performance. 3D printing materials absorb the same amount of solar energy as outdoor materials, but high insulation can reduce heat absorption, which leads to less reliance on active cooling systems during heating[32].

- **Emissivity:** refers to the material's ability to radiate heat from outdoors, where radiant heat exchange is common, understanding emissivity helps evaluate 3D printed buildings of overall performance monitoring [19].

VI. 3D PRINTED BUILDING APPLICATION ON THE EFFECT OF THE INSULATION MATERIALS AND ENHANCING ENERGY EFFICIENCY

Within the realm of 3D-printed building applications, the selection and utilization of insulation materials represent a pivotal aspect in determining energy efficiency. This section delves into the multifaceted effects of insulation materials within the context of 3D printed construction, elucidating their role in enhancing energy efficiency and thermal performance.To obtain a more extensive evaluation of the role of 3D printed concrete structuresthrough the climate crisis, it is imperative to quantify the effects of insulation materials on the energy efficiency and sustainability performance of 3DP buildings[2].

A. Insulation Materials Contribution to Maintaining Optimal Indoor Temperatures

Insulation materials play a crucial role in maintaining optimal indoor temperatures within buildings, including those constructed using 3D printing technology.Through an analysis of insulation potentials, mentioning some of them:

1. **Thermal Resistance:** Effective insulation materials possess high thermal resistance, which minimizes the flow of heat through walls, ceilings, and floors, thus stabilizing indoor temperatures[30].

2. **Reduced Energy Consumption:** By reducing the need for heating and cooling systems, insulation materials lower energy consumption and utility costs associated with maintaining indoor comfort levels[15].

3. **Enhanced HVAC Efficiency:** Insulation reduces the workload on HVAC systems by minimizing heat loss or gain, allowing heating and cooling systems to operate more efficiently and effectively.

B. Selection of Insulation Materials

Building envelope insulation is vital for the thermal and energy efficiency of a building because the envelope accounts for 50–60% of total heat gained and lost in the structure[2]. The selection process of the insulation materials considered in this study is based on their importance in the construction field and their great performance in several aspects[31]:

- life-cycle costs
- reusability
- thermal, mechanical, and moisture-resistant behavior.

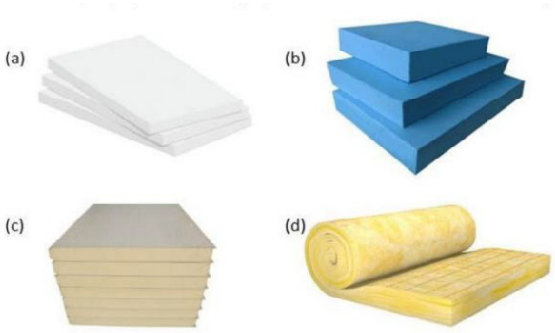


Fig. 4Insulating materials: (a) Expanded polystyrene boards (b) Extruded polystyrene boards; (c) Polyurethane foam insulation panels; (d) Fiberglass roll sheet[32].

C. Evaluating the insulation materials' performance

In our research, we have extensively reviewed multiple references that have examined and studied the impact of insulation materials on energy efficiency within building construction. Throughout our investigation, we have synthesized findings from various scholarly articles, reports, and studies focusing on this crucial aspect of building performance.

In particular, this section of our paper draws upon the results of a comprehensive study that validates the effects of different insulation materials on both thermal comfort and energy efficiency. Thisstudy examined the energy efficiency, carbon emissions, and thermal comfort of three insulated3DPCwalls with distinct mix designs. However, this paper will be focusing and limited on theresults of energy efficiency

and thermal comfort parts[32].

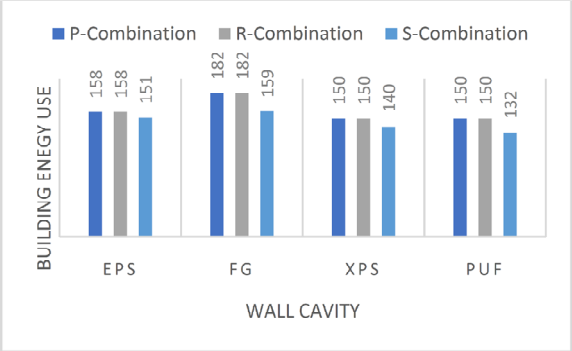


Fig. 5Insulation effect on 3DPC building energy use

The analysis stated that insulated building envelopes help reduce energy use. FG-insulated walls consume more energy than other models. EP Sand XPS and PU foam insulated envelopes are more efficient than FG-insulated walls, with PU foam being the most energy-efficient. InsS-4 is the optimal choice, saving 9500 KW more energy than control models and 1400 KW more than insulated walls[32].

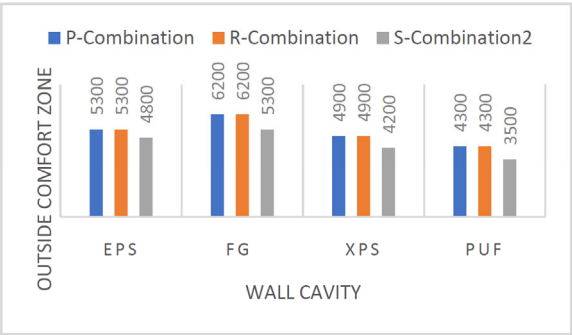


Fig. 6Effect of insulation on 3DPC thermal comfortefficiency.

The observed trend among the insulated models is similar to their energy-saving performance. Typically, long periods of thermal discomfort require proportionate measures of energy expenditure for temperature regulation. The air cavity wall models averaged 160 hours more discomfort hours than insulated walls, meaning that more hours of mechanical heating and cooling were required by the occupants within the uninsulated enclosure[32].

VIII. CONCLUSION

In conclusion, 3D printing technology has the potential to revolutionize traditional construction practices, offering sustainable solutions that mitigate environmental impact while prioritizing occupant well-being. The integration of insulation materials within 3D printed structures can optimize energy efficiency and thermal comfort. Insulation materials regulate indoor temperatures, reduce energy consumption, and foster environments conducive to occupant comfort. Selecting appropriate materials and deployment techniques is crucial to maximize energy performance and thermal resilience. Each insulation material offers distinct advantages in terms of thermal conductivity, moisture management, and overall energy efficiency.Insulation strategies require appropriate materials and techniques for energy efficiency. Fiberglass, EPS, and PU foam have different advantages in thermal conductivity, moisture management, and energy performance.By embracing innovation, fostering interdisciplinary collaboration, and prioritizing sustainability, we can forge a path toward a greener, more equitable future for generations to come.

REFERENCES

[1] F. S. ÜĞÜTMEN, "Climate Change Impact on a 3D Printed Concrete Building," 2023.
[2] A. H. Alami, A. Olabi, M. Ayoub, H. Aljaghoub, S. Alasad and M. A. Abdelkareem, " 3DConcrete Printing: Recent Progress, Applications, Challenges, and Role in Achieving Sustainable Development Goals," 2023.
[3] A. Urbinati, S. franzò, C. Sassanelli, P. Rosa, D. Chiaroni and S. Terzi, "Exploiting 3-D Printing for Designing Circular Business Models: A Novel Framework," 2023.
[4] Z. Wang, R. Song, H. Xiao, Y. Wang, G. Jiang, S. HU and C. Zhang, "Terrestrial heat flow of Jizhong depression, China, Western Bohai Bay basin and its influencing factors," 2021.
[5] M. Diesendorf, "Sustainability and sustainable development," 2000.
[6] A. Griffiths, D. Dunphy and S. Benn, "Organizational change for corporate sustainability, Third edition," 2014.
[7] J. M. Pearce, I. Zelenika and A. Buitenhuis, "Open design-based strategies to enhance appropriate technology development," 2010.
[8] M. Khorasani, B. Stucker, D. Rosen and I. Gibson, Additive Manufacturing Technologies, Springer Cham, 2021.
[9] C. Folke, K. Takeuchi , O. Gaffney, P. Olsson, T. McPhearson and T. Elmqvist, Sustainability and resilience for transformation in the urban century, 2019.
[10] B. Georgios, N. Moussiopoulos, C. Vlachokostas and C. Achillas, "Decision support system for the optimal location of electrical and electronic waste treatment plants: A case study in Greece," 2010.
[11] R. Ramlan, T. Lee and N. Shahrubudin, "An Overview on 3D Printing Technology: Technological, Materials, and Application," 2019.
[12] Q. Wang, J. Gu and T. An , "The emission and dynamics of droplets from human expiratory activitiesand COVID-19 transmission in public transport system: A review," 2019.
[13] T. Reinicke and M. . R. Khosravani, "On the environmental impacts of 3D printing technology," 2020.
[14] A. Sodiq, M. . A. Khan, M. Naas and . A. Amhamed, "Addressing COVID-19 contagion through the HVAC systems by reviewing indoor airborne nature of infectious microbes: Will an innovative air recirculation concept provide a practical solution?," 2021.
[15] B. Goldberg, K. Gupton, K. Hellman, R. Robson, S. Blake-Plock and M. Hoffman, "Forging Competency and Proficiency through the Synthetic Training Environment with an Experiential Learning for Readiness Strategy," 2021.
[16] R. Varatharajan , D. Parthiban , J. Revathy, A. Mohan and D. Vijayan, "Evaluation of the impact of thermal performance on various building bricks and blocks: A review," 2021.
[17] M. Szabó and Q. Al-Yasiri, "Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis," 2021.
[18] M. Rehm and R. Ade, "The unwritten history of green building rating tools: a personal view from some of the 'founding fathers'," 2019.
[19] V. Marinakis, "Big data for energy management and energy-efficient buildings," 2020.

[20] F. Feng, N. Kunwar, K. Cetin and Z. O'Neill, "A critical review of fenestration/window system design methods for high performance buildings," 2021.
[21] A. Raouf and S. G. Al-Ghamdi, "Framework to evaluate quality performance of green building delivery:construction and operational stage," 2023.
[22] F. Favoino, R. C. Loonen, M. Michael, G. D. Michele and S. Avesani, "Advanced fenestration—technologies, performance and building integration," 2022.
[23] J. Chiavaroli, Comprehensive and Integrative Architectural Design, 2022.
[24] N. B. Ziyadanogullari, H. Yucel and C. Yildiz, "Thermal performance enhancement of flat-plate solar collectors by means of three different nanofluids," 2018.
[25] N. Mariotti, M. Bonomo, L. Fagiolari, N. Barbero, C. Gerbaldi, F. Bella, C. Barolo and F. Bella, "Recent advances in cost-effective and eco-friendly materials towards sustainable Dye-sensitized solar cells," 2020.
[26] P. Ramesh and A. Bharani, "Smart Sustainable Cities: Principles and Future Trends," 2022.
[27] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," 2017.
[28] L. L. Rajamony , B. Gurupatham, K. Roy and J. Lim, "Effect of super absorbent polymer on microstructural and mechanical properties of concrete blends using granite pulver," 2020.
[29] G. Gonzalez, I. Roppolo, C. F. Pirri and A. Chiappone, "Current and emerging trends in polymeric 3D printed microfluidic devices," 2022.
[30] A. Vijayan, R. Tofanelli, S. Strauss, L. Cerrone, A. Wolny, J. Strohmeier, A. Kreshuk, F. . A. Hamprecht, R. . S. Smith and K. Schneitz, "A digital 3D reference atlas reveals cellular growth patterns shaping the Arabidopsis ovule," 2021.
[31] M. Wuttig, C.-F. Schön, J. Lötfering, . P. Golub, . C. Gatti and . J.-Y. Raty, "Revisiting the Nature of Chemical Bonding in Chalcogenides to Explain and Design their Properties," 2022.
[32] B. . O. Ayegba, K.-J. . I. Egbe, A. M. Nazar , M. Huang and M. A. Ardebili , "Resource Efficiency and Thermal Comfort of 3D Printable Concrete Building Envelopes Optimized by Performance Enhancing Insulation: A Numerical Study," 2022.

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