Review of Sustainable Cooling Technologies for Buildings

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ABSTRACT

This paper investigates the field of environmentally friendly cooling systems and how they might be used in business buildings. Understanding these technologies, evaluating their efficacy, and making judgments about their acceptability are the goals. Four major sustainable cooling technologies—green roofs, radiant cooling systems, thermal energy storage, and natural ventilation—are covered in detail in the literature study.

Green roofs have cooling properties that counteract the urban heat island effect because they grow flora on building surfaces. Energy-efficient heat removal is achieved via radiant cooling systems through the use of panels or chilled beams. In order to reduce energy consumption, thermal energy storage devices store extra thermal energy during off-peak hours. Natural ventilation techniques lessen reliance on mechanical cooling by utilizing stack effect and cross-ventilation.

Environmental effect, financial concerns, and energy efficiency are all taken into account in the study. Green roofs and radiant cooling technologies both show significant energy savings and beneficial environmental consequences. While differing amongst technologies, cost-effectiveness indicates long-term operational savings. Green roofs and radiant cooling systems are environmentally favorable, according to environmental impact evaluations.

In summary, the selection of sustainable cooling technology must to be in line with particular building specifications and limitations. Research and innovation in these technologies will probably lead to more eco-friendly and efficient commercial building solutions as global sustainability initiatives pick up steam, resulting in durable and energy-efficient structures for a sustainable future.

Keyword: *- Sustainability, Cooling Techniques, Building, Relative Importance Index (RII)*

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1. Introduction

Growing urbanization, rising temperatures, and rising income are driving up the need for cooling in buildings, which is a major challenge in India. Because traditional cooling systems are often energy-intensive and rely on ecologically toxic refrigerants, they are placing further strain on the already overburdened electrical infrastructure in the country and increasing greenhouse gas emissions. Given this situation, a thorough examination of environmentally friendly cooling techniques for Indian buildings is required.

India faces unique challenges in adopting and implementing sustainable cooling technologies due to its unequal infrastructure development and diverse range of temperature zones. The need for cooling is most pressing in the commercial, residential, and industrial sectors, where traditional air conditioning systems are common but come with substantial energy and environmental costs.

With India's National Action Plan on Climate Change attesting to its commitment to sustainability, a move to ecologically friendly cooling techniques is also required (NAPCC). Consequently, the issue statement focuses on identifying, evaluating, and advocating for sustainable cooling solutions that are energy-efficient and workable in India from a cultural, economic, and environmental perspective.

2. Objectives

- Identify promising sustainable cooling technologies for buildings.
- Analyze each sustainable cooling technology for buildings based on environmental, social, and economic criteria.
- Determine the most suitable sustainable cooling technology for buildings considering all identified criteria.

3. Sustainable Cooling Technologies for Buildings: A Comprehensive Review

The search for green building cooling systems has intensified as concerns over energy use and climate change spread around the world. In this review of the literature, we investigate the evolving landscape of sustainable cooling systems by analyzing the existing research and advancements.

3.1 Passive Cooling Techniques

Natural Ventilation: Natural ventilation is one of the most significant passive cooling strategies. It uses carefully placed apertures to encourage the flow of outside air by utilizing architectural characteristics. Research by [12] shows that natural ventilation is effective in reducing indoor temperatures and energy use in both residential and commercial buildings. The study highlights how consuming less energy and increasing indoor comfort is possible with passive cooling. [10]
Natural ventilation is an efficient way to lower indoor temperatures and save energy by using architectural features that allow outside air circulation [12] [10]

Night Ventilation: Through the use of night ventilation systems, colder exterior air is drawn in at night and stored in the thermal mass of the building to provide cooling during the day. [10] conducted a thorough review of night ventilation strategies with an emphasis on possible energy savings. The significance of night ventilation for enhancing energy efficiency and reducing peak cooling needs is emphasized in the study.
Using this method, you can store cooler outdoor air for use during the day by bringing it inside a structure's thermal mass at night. Its potential to increase energy efficiency is highlighted by research [10]

Cool Roofs: Cool roofs, which are composed of materials with high albedo or reflection properties, reduce the impact of the urban heat island effect. A landmark study by [4] evaluated the cooling energy savings potential of cool roofs in both residential and commercial buildings. Their research demonstrates how climate-responsive and energy-efficient cool roofing materials are.
These reflective roofs provide climate responsiveness and energy efficiency by reducing the urban heat island effect [4]

3.2 High-Efficiency HVAC Systems

Variable Refrigerant Flow (VRF): By controlling many zones simultaneously, variable frequency functions (VRF) optimize energy consumption through their dynamic cooling and heating approach. [2] conducted a thorough review of VRF systems in 2019 with an emphasis on how they may increase comfort while consuming less energy. The study focuses on the role that VRF systems play in efficiently heating and cooling buildings.
A dynamic method to heating and cooling that maximizes energy efficiency [2].

Energy Recovery Ventilation (ERV): Energy Recovery Ventilators (ERVs) improve indoor air quality and save energy for the HVAC system by recovering heat and moisture from exhaust air. (P. Bansal, 2020) conducted a comprehensive analysis of ERV systems and showed how they may enhance both energy efficiency and occupant comfort. The study underlines how important ERV systems are to the cooling of ecologically friendly buildings.
Improving indoor air quality while reducing HVAC system energy usage [11].

Smart Thermostats: According to occupancy and ambient conditions, smart thermostats with remote control and learning algorithms provide better cooling. In 2018, H. Li conducted a review of smart thermostat technologies,

emphasizing its potential to reduce energy consumption in residential buildings. The study emphasizes how smart thermostats may be used to precisely and economically cool spaces.
Optimizing energy-efficient cooling in residential buildings with the integration of remote control and learning algorithms [5].

3.2 Integration of Renewable Energy

Geothermal Cooling: Effective cooling is produced by geothermal cooling, which makes use of the earth's steady temperature. [9] studied ground-source heat pumps and their applications in cold climates, emphasizing their potential for energy-efficient building heating and cooling. The year-round benefits of geothermal cooling are emphasized in the study.
making use of the earth's constant temperature to cool in a sustainable and efficient manner [9].

Solar Cooling: Solar cooling systems, such as adsorption and absorption chillers, employ solar radiation to provide cooling without the need for power. [3] examined solar cooling technologies and underlined how energy-efficiently they may be used to cool buildings. The durability of solar cooling systems is emphasized in the research.
using solar power to cool without using electricity and focusing on long-term effectiveness [3].

3.3 Thermal Energy Storage (TES)

Ice-Based TES: Ice-based thermal energy storage systems generate cooling during off-peak hours and store it as ice for later use. The usage of ice-based TES systems was studied in 2016 by [7], who concentrated on the systems' ability to reduce cooling energy consumption and boost energy efficiency.
lowering the amount of energy needed for cooling by storing thermal energy in ice [7].

Phase Change Materials (PCMs): PCMs absorb and release heat to help maintain consistent interior temperatures and reduce the demand for continuous air cooling. [8] reviewed PCMs in cold thermal energy storage applications and noted that they might improve occupant comfort and cooling efficiency.
absorbing and releasing heat to keep the inside temperature steady and do away with the continuous requirement for air conditioning [8].

3.4 Emerging Strategies

Radiant Cooling: Radiant cooling systems circulate cool water through pipes or panels positioned on walls and ceilings to effectively absorb and disperse heat.[6] conducted research on radiant cooling systems and found that they have the ability to provide comfortable, energy-efficient cooling.
effectively collecting and releasing heat through water pipes to provide cooling that is both comfortable and energy-efficient [6].

Green Roofs and Walls: Green roofs and walls covered with vegetation reduce heat absorption and serve as insulation. The impact of green roof thermal behavior on a building's energy efficiency has been studied [1]. The study emphasizes how natural cooling may be aided by green rooftops and walls.
Structures covered with vegetation serve as insulation, improving a building's energy efficiency [1].

4. Important factor to analyzing sustainable cooling technology:

When researching sustainable cooling techniques for buildings, several important factors need to be taken into account. Take into consideration the following crucial components for more research.

Environmental Impact: When evaluating the environmental effects of sustainable cooling technology, take into account its ability to lower greenhouse gas emissions, carbon footprint, and compatibility with low global warming potential (GWP) refrigerants [13].

Economic Viability: [2] investigate the long-term energy cost reductions, continuing expenditure expenses, and initial investment costs when assessing the cost-effectiveness of using sustainable cooling systems.

Comfort and Indoor Air Quality: Take into account how the cooling technology will impact interior comfort and air quality in order to maintain or enhance occupant well-being [11].

Resilience to Climate Change: Long-term operation requires consideration of the technology's ability to withstand and adjust to changing climatic conditions [9].

Scalability and Applicability: Evaluate how effectively the system works in different climates and geographical locations, and how scalable it is for different types and sizes of buildings [10].

Maintenance and Scalability: Assessing the technology's suitability for a range of climates and geographical regions, as well as its scalability for different types and sizes of buildings and potential future extension of the current structure [10].

Regulatory Compliance: Ensure that the technology complies with construction guidelines, energy efficiency regulations, environmental standards, and regional regulatory compliances [13].
Technological Advancements: Stay up to date on the latest technical advancements and novel technologies in sustainable cooling to maximize the benefits of state-of-the-art solutions [3].

User Satisfaction and Feedback: Get input from building managers and tenants to find out more about their satisfaction levels with the cooling system and to identify areas that might want improvement.

5. Research Methodology

Introduction:
This chapter describes the study process used to determine which sustainable cooling system is most appropriate for buildings. The process has several phases, such as designing the survey, gathering data, analyzing it, and interpreting the results. The goal is to compile in-depth information about the interests and preferences of industry professionals with regard to sustainable cooling technology.

Research Design:
The study used a quantitative methodology, gathering information from specialists in the field using a structured questionnaire survey. The purpose of the poll was to evaluate participants' opinions on various environmentally, socially, and economically responsible cooling systems. In order to learn more about the respondents' backgrounds and level of awareness, the questionnaire asked demographic questions. Next, rating scales were used to determine how important different cooling technologies and criteria were.

Sampling:
Professionals from the built environment business, such as architects, engineers, facilities managers, and sustainability specialists, made up the sample frame. Participants were chosen using a convenience sample approach, taking into account their accessibility and desire to participate. In order to include a wide variety of viewpoints, efforts were taken to guarantee sample diversity.

Data Collection:
An online survey platform was used for data collection, giving participants the flexibility to complete the questionnaire whenever it was convenient for them. Social media, professional networks, and email invites were all used to share the survey link. To guarantee the quality and dependability of the data, participants were urged to give candid and deliberate answers.

Data Analysis:

The survey's data offers insightful information on the opinions and preferences of specialists in the field with regard to environmentally friendly building cooling systems. The purpose of this section's analysis of the replies is to spot trends, patterns, and places where participants agree and disagree.

Experience in the Industry:
People with less than a year to more than 10 years of experience in the sector were among those whose replies were collected for the study. To determine whether experience and desire for technology are correlated in any way, replies from respondents in various experience brackets will be analyzed.

Type of Construction Company and Job Position:
A wide spectrum of construction organizations, including general contractors, consulting firms, owner/clients, and architecture/design firms, were represented by the participants. In a similar vein, occupations ranged from senior architects and CEOs to undergraduates and project engineers. Responses categorized by job title and firm type may be analyzed to provide information into how various industrial positions see sustainable cooling solutions.

Awareness Level about Sustainable Cooling Technologies:
The participants rated their own level of awareness regarding sustainable cooling systems. Determining how familiar industry experts are with these technologies and how it could affect their choices will be made easier by analyzing the distribution of awareness levels.

Effectiveness of Cooling Technologies:
Answers to questions on the relative merits of various cooling systems—such as geothermal, solar, and natural ventilation—give information about which technologies experts in the field believe to be most efficient.

Cost-effectiveness and Maintenance:
The cost-effectiveness and maintenance needs of different cooling methods were appraised by the participants. By examining these answers, industry experts' suggested low-maintenance and cost-effective solutions will be found.

Technology Preference:
Participants were asked to choose the sustainable cooling system that, in their opinion, best fits building needs while taking into account all relevant factors (economic, social, and environmental). Which technology is preferred by the majority of participants will be revealed by analyzing the distribution of preferences.

Below given are the responses received from the industry experts and peoples and recorded in tabular form after giving equal weightage to each factor.

Table 1: Sample Data Part-I

S. No.	Natural Ventilation	Solar Cooling	Geothermal Cooling	Green Roofs and Walls	Passive Cooling Techniques	High-Efficiency HVAC Systems
1	3	2	2	2	2	3
2	1	1	1	2	1	1
3	2	2	3	3	3	3
4	3	2	4	1	1	3
5	2	3	3	2	2	4
6	3	3	2	2	3	3
7	2	3	2	3	3	2
8	1	2	1	1	2	3
9	1	3	1	3	3	1
10	2	2	2	1	3	2
11	3	3	4	3	3	2

12	3	3	3	3	4	3
13	4	3	3	3	3	2
14	3	2	1	2	2	2
15	1	2	1	2	4	2
16	2	2	1	3	3	4
17	4	3	2	3	3	3
18	2	2	2	2	2	2
19	3	3	3	4	3	2
20	1	1	1	1	3	3
21	3	2	3	3	3	2
22	4	4	4	3	4	2
23	2	3	2	3	3	3
24	3	3	2	4	1	2
25	3	3	4	4	3	3
26	3	3	1	1	2	3
27	2	2	2	2	2	2
28	2	2	2	1	3	3
29	3	2	2	2	2	3
30	1	1	1	2	1	1
31	2	2	3	3	3	3
32	3	2	4	1	1	3
33	2	3	3	2	2	4
34	3	3	2	2	3	3
35	2	3	2	3	3	2
36	1	2	1	1	2	3
37	1	3	1	3	3	1
38	3	2	2	2	2	3
39	1	1	1	2	1	1
40	2	2	3	3	3	3
41	3	2	4	1	1	3
42	2	3	3	2	2	4
43	3	2	2	2	2	3
44	1	1	1	2	1	1
45	2	2	3	3	3	3
46	3	2	4	1	1	3
47	2	3	3	2	2	4
48	3	3	2	2	3	3
49	2	3	2	3	3	2
50	1	2	1	1	2	3
Average	2.28	2.36	2.24	2.24	2.4	2.58

Total Possible Score	200	200	200	200	200	200
Relative Importance Index (RII)	**4.56**	**4.72**	**4.48**	**4.48**	**4.8**	**5.16**

Table 2: Sample Data Part-II

S.No.	**Radiant Cooling**	**Wind-Catcher Towers**	**Ice-Based Thermal Energy Storage**	**Effectiveness of Solar Cooling Systems**	**Maintenance Costs of Geothermal Cooling Systems**
1	2	2	2	2	2
2	2	3	1	1	1
3	3	3	3	3	2
4	2	4	2	1	2
5	4	2	1	4	3
6	3	2	2	2	2
7	3	4	2	2	2
8	2	1	2	2	3
9	3	1	3	1	2
10	1	1	1	1	2
11	3	2	3	2	3
12	4	3	3	4	1
13	2	2	2	2	2
14	2	1	2	1	2
15	2	1	1	1	2
16	1	2	2	2	2
17	2	2	1	2	3
18	2	2	2	2	3
19	1	3	3	3	2
20	2	1	1	3	2
21	3	2	2	3	2
22	2	1	2	2	2
23	3	2	2	2	2
24	1	2	2	2	2
25	4	3	3	4	2
26	2	2	1	2	1
27	2	2	2	2	2
28	3	1	2	2	2
29	2	2	2	2	2
30	2	3	1	1	1
31	3	3	3	3	2
32	2	4	2	1	2
33	4	2	1	4	3
34	3	2	2	2	2
35	3	4	2	2	2
36	2	1	2	2	3

37	3	1	3	1	2
38	2	2	2	2	2
39	2	3	1	1	1
40	3	3	3	3	2
41	2	4	2	1	2
42	4	2	1	4	3
43	2	2	2	2	2
44	2	3	1	1	1
45	3	3	3	3	2
46	2	4	2	1	2
47	4	2	1	4	3
48	3	2	2	2	2
49	3	4	2	2	2
50	2	1	2	2	3
Average	2.48	2.28	1.94	2.12	2.08
Total Possible Score	200	200	200	200	150
Relative Importance Index (RII)	**4.96**	**4.56**	**3.88**	**4.24**	**4.16**

Chart 2: Response Data Chart

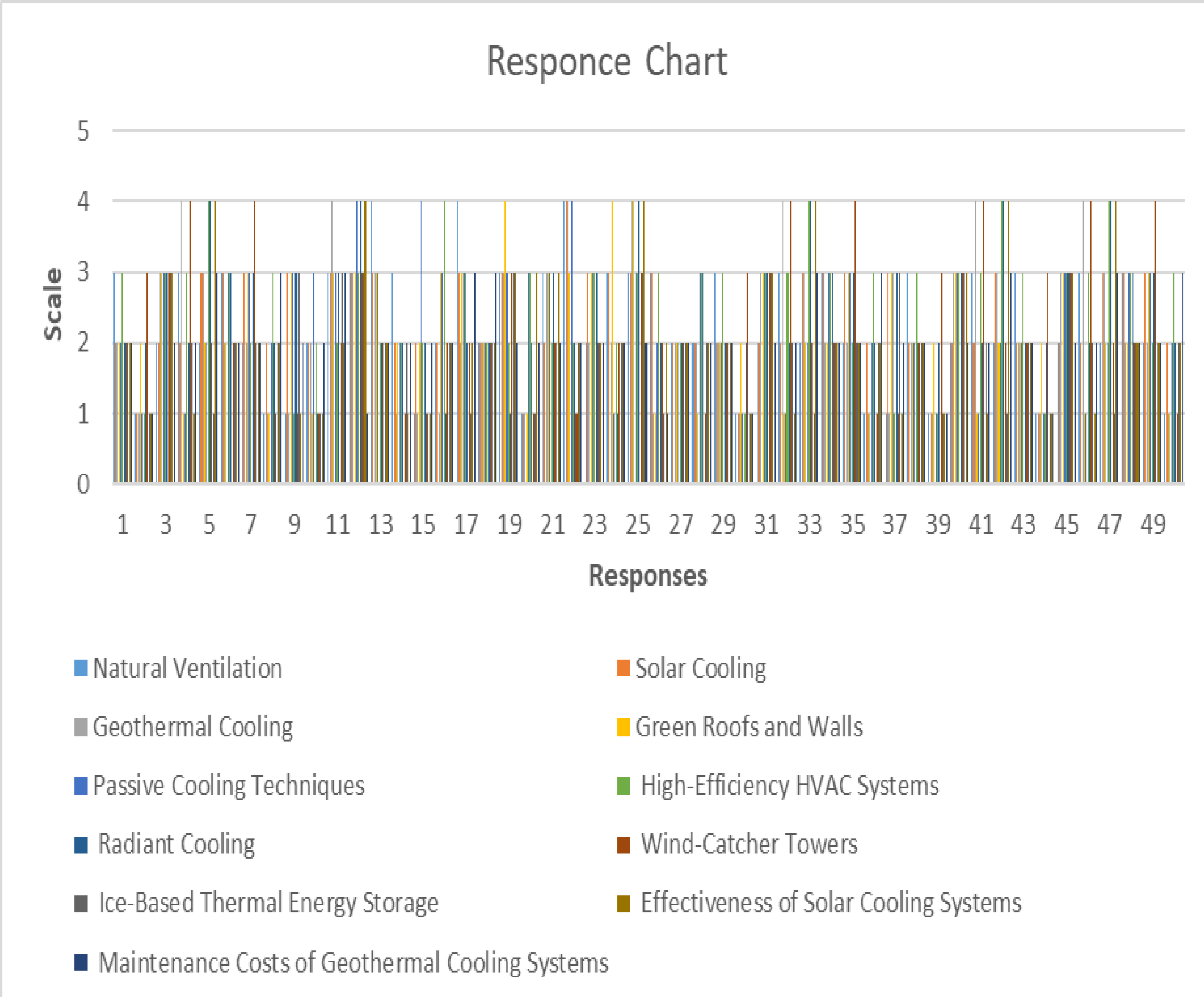


Chart 2: Relative Importance Index (RII) Data Chart

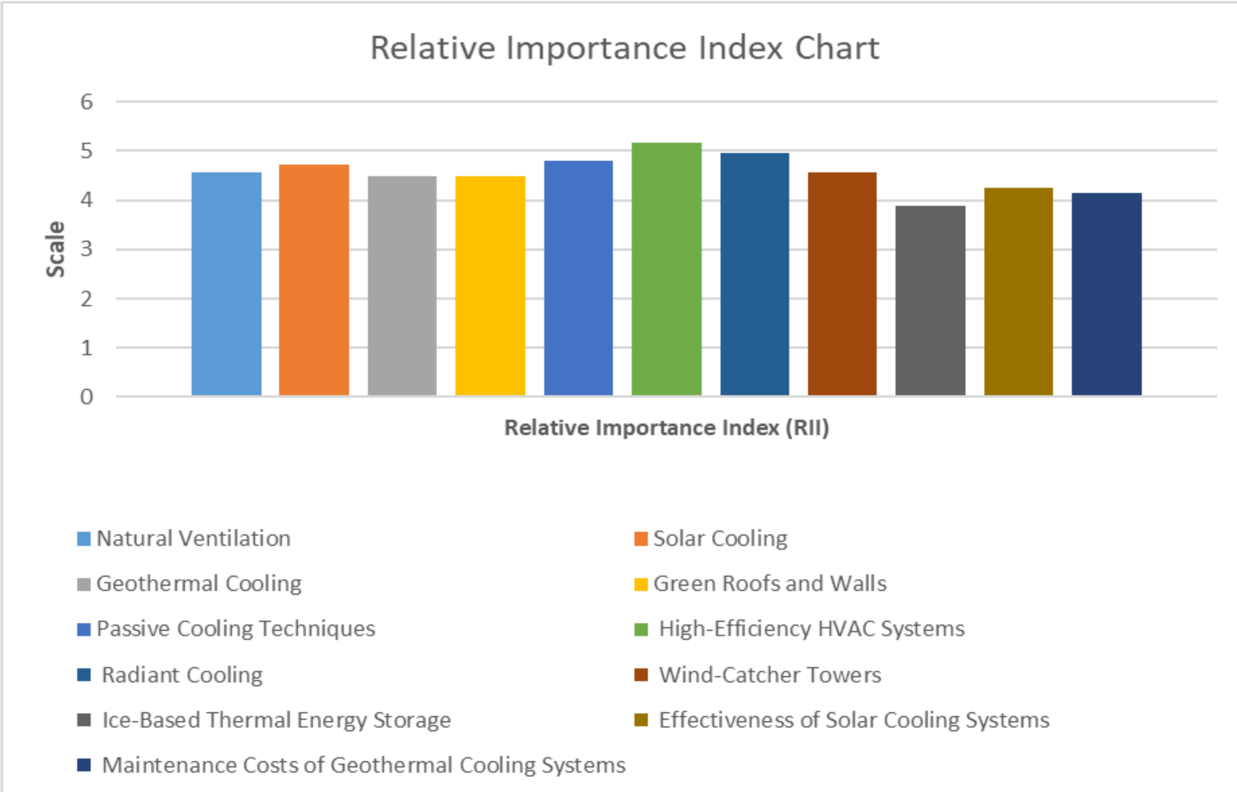
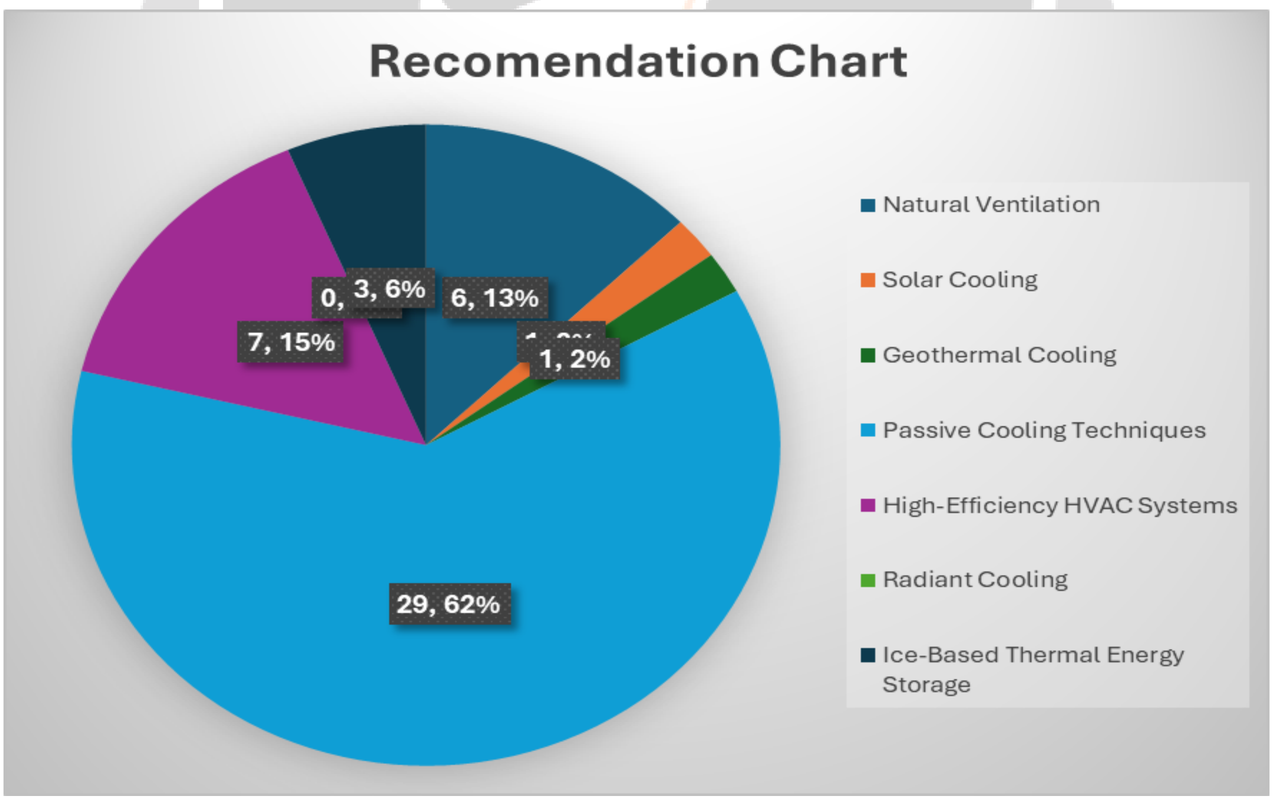


Chart 2: Recommendation Chart



We may make numerous inferences from the survey results, the Relative Importance Index (RII) ratings that were computed for each sustainable cooling technique, and the suggestions that were offered:

Analysis of Relative Importance Index (RII) Scores:

According to survey respondents' answers, the RII ratings show the relative significance of each sustainable cooling technique.
The respondents regarded high-efficiency HVAC systems as the most significant sustainable cooling technology, as shown by their highest RII score of 5.16.
Indicating their critical role in sustainable cooling solutions, other technologies including solar cooling, passive cooling techniques, and radiator cooling also scored highly on the RII.
With a RII score of 3.88, which is comparatively lower than other technologies, Ice-Based Thermal Energy Storage appears to be overlooked in comparison.

Recommendations:

The number of respondents who thought that each sustainable cooling technique was the best choice is indicated by the recommendation ratings.
With a recommendation score of 29, passive cooling techniques were found to be the most often suggested sustainable cooling solution among survey respondents.
Notable recommendation ratings were also given to natural ventilation and high-efficiency HVAC systems, demonstrating that these solutions are also commonly regarded as viable choices for sustainable cooling.
With a recommendation score of 0, Radiant Cooling was shown as not being suggested by any survey respondents.

6. Conclusion

The survey's findings emphasize how crucial it is to take into account a range of sustainable cooling technologies when developing and putting into practice building cooling solutions.
Based on RII ratings, high-efficiency HVAC systems were found to be the most significant technology; yet, respondents strongly preferred passive cooling techniques, which yielded the highest recommendation score.
Significant attention was also paid to solar and geothermal cooling, indicating these technologies' potential use in sustainable cooling applications.
There is a need for more research into the variables influencing preferences and perceptions of sustainable cooling technologies, as seen by the disparity between RII scores and recommendation ratings for some technologies, such as radiant cooling.
As building cooling solutions are designed and implemented, it is critical to take into account a range of sustainable cooling technologies, as shown by the survey results.
Passive cooling techniques obtained the greatest recommendation score, showing a strong preference among respondents, whereas high-efficiency HVAC systems emerged as the most significant technology based on RII ratings.
Additionally, solar and geothermal cooling attracted a lot of attention, indicating their potential use in sustainable cooling applications.
More research is necessary to determine the elements influencing people's choices and perceptions of sustainable cooling technologies, as seen by the gap between RII ratings and recommendation scores for some systems, such radiant cooling.

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