Bio-jaali: Passive building skin with mycelium for climate change adaptation to extreme heat

Kumar Biswajit Debnath[1], Natalia Pynirtzi[1], Jane Scott[1], Colin Davie[2], Ben Bridgens[1]
[1]Hub for Biotechnology in the Built Environment, School of Architecture, Planning and Landscape, Newcastle University, Newcastle Upon Tyne, United Kingdom
[2]School of Engineering, Newcastle University, Newcastle Upon Tyne, United Kingdom

Abstract

Climate change induced global warming and frequent extreme heat events have become common recently, increasing the ownership and operation of active cooling, particularly in cities and megacities. To reduce the dependency on active cooling, in this study, we aimed to re-design 'Jaali'— perforated screens made of bricks and sandstones to cool the incoming air inspired by historical building use— with bio-based materials such as mycelium. We hypothesised that 'Bio-jaali' would ventilate and reduce the indoor temperature reducing energy demand for cooling. For the climatic context, we selected the temperate climate of New Delhi. We used climatic data analysis and performance-based dynamic environmental simulations with Designbuilder and Energy Plus to evaluate the effect of Bio-jaali on the indoor operative temperature in a single-zone naturally ventilated indoor office space. The simulation results showed sandstone Jaali reduced the annual average indoor operative temperature by 5.2%, whereas Bio-jaali were able to provide a reduction of 3.0% compared to the base case. Furthermore, the seasonal analysis showed that Bio-jaali reduced the summer indoor operating temperature by decreasing heat gain from outdoor heat, particularly during daytime and increased indoor temperature during winter by reducing heat loss, demonstrating its potential for year-round usage.

Highlights

- Re-designing 'Jaali' with bio-based materials
- Demonstrated potential in reducing the indoor operative temperature in the temperate climate of New Delhi, India
- Showed potential in tackling extreme heat events
- Potential of year-round usage.

Introduction

Of 33 Global Megacities (UN, 2018)— with a population of more than 10 million — ten are in South Asia. According to the UN, New Delhi will be the largest megacity globally, with Dhaka and Mumbai in the top ten megacities by 2030 (a predicted total of 43) (UN, 2018). Also, extreme heatwaves are increasing due to climate change in South Asia (IPCC, 2022), becoming an annual phenomenon. Therefore, billions of people have been living with the adverse effects of extreme heat in South Asian megacities (Debnath, et al., 2022). Extreme heat exposure might cause severe health issues ranging from heat exhaustion, cramps, heat stroke, and even death (NIH, 2022). People tend to use air conditioning (A/C) for comfort and sometimes survival which is projected to increase, elevating electricity demand for space cooling (Debnath, et al., 2020). For example, India will have 240 million A/C units by 2030, reaching 1144 million by 2050 (IEA, 2019), from 21.8 million in 2017 (GoI, 2015). For developing resilience to extreme heat events in buildings, it's becoming essential to re-think the passive building skin design to reduce dependency on active energy-based cooling solutions.

This study aimed to re-design 'Jaali' (Prasad, et al., 2022)— perforated screens made of bricks and sandstones (and laterite and khondalite) to cool the incoming air inspired by distinct architectural features in India between the 16th and 18th Centuries — with bio-based materials such as mycelium. 'Bio-jaali' would ventilate and reduce indoor operative temperature passively in the climatic context of New Delhi. This study used climatic data analysis and performance-based dynamic environmental simulations with Designbuilder and Energy Plus.

Methodology

As a climatic context, we focused on the temperate climate in New Delhi, India. The study had three major parts: climate analysis, building thermal model development, and additional Jaali scenario testing and analysis. Firstly, New Delhi's climate data for 1985-2021 were analysed to investigate the prevalence of heat stress using Equations 1 and 2. Secondly, we developed the building physics model of an area of 100 m^2 indoor space (in Designbuilder) with a double-layer curtain wall on the south façade. In the third stage, four scenarios were assessed within the simulation environment (with EnergyPlus) to determine the effect of different building screens on the indoor operative temperature. EnergyPlus was previously used in a significant number of studies regarding building physics and thermal comfort, such as (Xu, et al., 2014; Yoon, et al., 2014; Al-janabi, et al., 2019; Huang & Wu, 2019; Debnath & Jenkins, 2020), which motivated us to use the simulation environment.

Heat stress analysis

We obtained 36 years of weather data (1985-2021) from the Meteoblue database (www.meteoblue.com) for the Heat Index (HI) analysis of New Delhi. The ambient temperature and relative humidity data were used to calculate the hourly heat index (HI) with the following

https://doi.org/10.26868/25222708.2023.1516

Equation 1 adopted from (Rothfusz & Headquarters, 1990):

$$HI = -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - 6.83783 \times 10^{-3}T^2 - 5.481717 \times 10^{-2}R^2 + 1.22874 \times 10^{-3}T^2R + 8.5282 \times 10^{-4}TR^2 - 1.99 \times 10^{-6}T^2R^2 \ldots\ldots(1)$$

Where, T - Ambient dry bulb temperature (°F)

R - Relative humidity (integer percentage)

HI was selected for the study as it has been widely used in several studies to analyse the adverse effect of heat stress, such as (Luo & Lau, 2019; Modarres, Ghadami, Naderi, & Naderi, 2018; Choi & Lee, 2020; Opitz-Stapleton, et al., 2016). For the analysis in this study, we converted the ambient dry bulb temperature into °C with the following Equation 2 adopted from (Fay & Hardie, 2003):

$$C = 5/9\,(F - 32) \ldots\ldots (2)$$

Where C- Ambient dry bulb temperature (°C)

F- Ambient dry bulb temperature (°F)

Furthermore, we used the Heat Stress Index scale (Table 1) developed by National Oceanic and Atmospheric Administration (NOAA) (NWS, 2020) to evaluate the HI for New Delhi.

Table 1: Heat index and corresponding health impacts (NWS, 2020)

Heat Stress Index (°C)	Category	Dangers
27-32	Caution	Fatigue
32-41	Extreme caution	Sunstroke, heat cramps and heat exhaustion
41-54	Danger	Sunstroke, heat cramps and heat exhaustion, and even heat stroke
54+	Extreme danger	Heat/sunstroke

Building physics modelling

A single zone naturally ventilated indoor office space (with 100 m^2 area) was modelled (Figure 2) with 10m length, 10m width and 3m height in Designbuilder with constructions and materials described in Table 2. There was a curtain wall with double-layer glass on the South. A jaali was modelled 0.32m in front of the South façade (Figure 2). Considering the computational time and limits, the Jaali design was kept simple with repetitive square apertures (0.07m width) at 0.07m intervals. The thickness of the Jaali was denoted as Th_s, which varied with simulation scenarios. We used the 'Generic office template' and 0.1110 people/m^2 for the activity template. Also, we used office equipment with a power density of 11.77 W/m^2.

Three temporal analysis was conducted to evaluate the impact of the Bio-jaali on the indoor operative temperature. First, we analysed the effect annually. Secondly, we selected three dates in summer (1 April, 1 June, and 1 August) and winter (1 November, 1 January and 1 March) to evaluate the impact hourly. We assessed the outdoor and indoor operative temperatures against the India Model for Adaptive Comfort (IMAC) model, which suggested the neutral temperature in naturally ventilated buildings varied from 19.6-28.5 °C (Manu, et al., 2016).

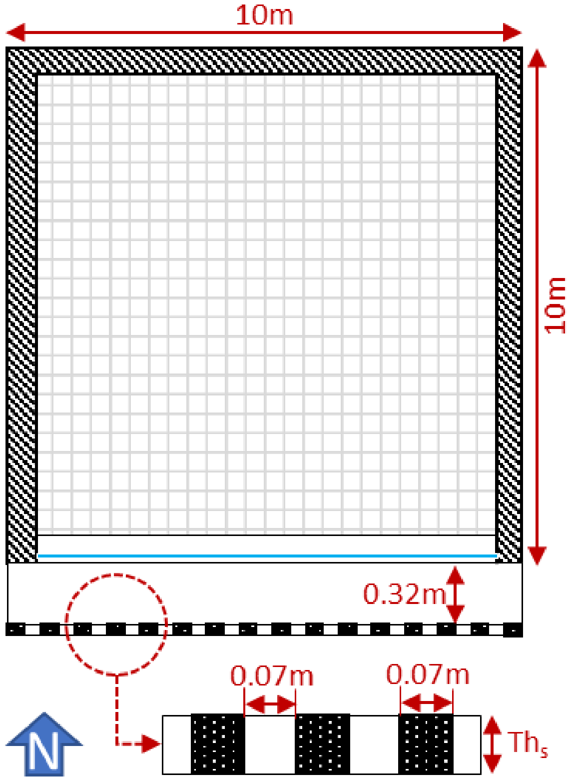

Figure 1: Plan of the indoor space for simulation (not to scale)

Table 2: Construction name, thickness, and materials; for the material properties, we used a software database

Name	Thickness (m)	Materials	U-Value (W/m^2-K)
Exterior walls	0.293	Brickwork, XPS extruded polystyrene, concrete block, and Gypsum plastering	0.350
Ground floor	0.333	Cast concrete (0.1m) with Urea Formaldehyde foam, floor screed and timber flooring.	0.264
Flat roof	0.368	Asphalt, glass wool, air gap and plasterboard	0.259
Curtain (glass) wall	0.019	Double-layer Glass windows with air gap and wooden frames	1.960

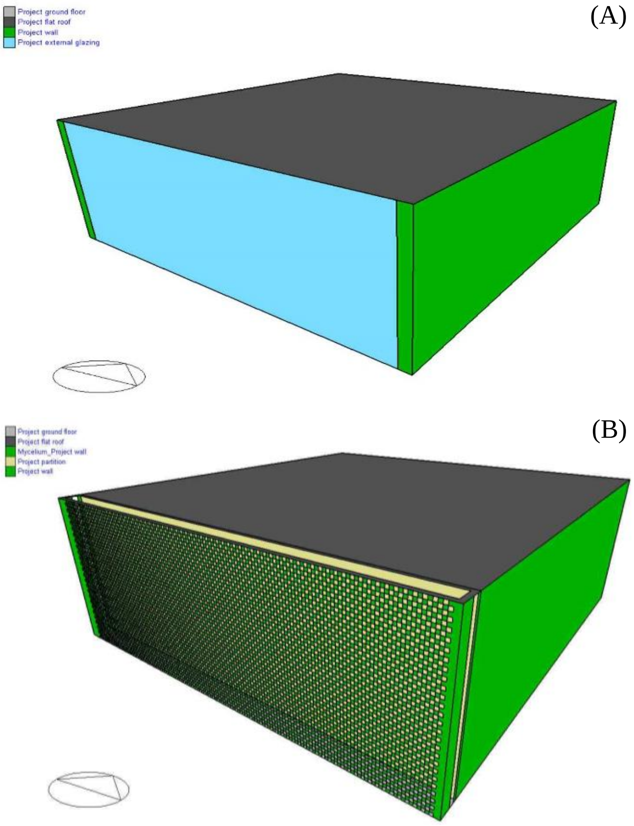

Figure 2: Building physics model of (A) without Jaali and (B) with Jaali, developed in Designbuilder (Version 7.0.2.006)

Scenario development

No Jaali was in front of the South façade in the base case. For the study, the following scenarios described in Table 3 and illustrated in **错误!未找到引用源。** were selected to test the effect of the proposed Bio-jaali on the indoor operative temperature.

Table 3: Jaali materials and thickness for the base case and other scenarios

Scenario	**Jaali in front of the South façade (Y/N)**	**Jaali material**	**Jaali thickness (*Th$_S$*)**
Base case	N	N/A	N/A
Sandstone Jaali (SJ)	Y	Sandstone	0.04m
Bio-jaali 1	Y	Mycelium	0.04m
Bio-jaali 2	Y	Mycelium	0.1m

For the Mycelium material in the IDF file for Energy Plus simulation, the conductivity, density and specific heat properties were used for Bio-jaali construction from (Zhang, et al., 2022):

"Material, Mycelium material,

Rough,	!- Roughness
Th$_S$,	!- Thickness {m}
0.069,	!- Conductivity {w/m-K}
599,	!- Density {kg/m3}
6894,	!- Specific Heat {J/kg-K}
0.9,	!- Thermal Emittance
0.6,	!- Solar Absorptance
0.6;	!- Visible Absorptance"

Results

Heat stress

In the case of the capital city New Delhi (India), the maximum HI was 51.92°C in 2019, the highest since 1991, 1.8°C and 2°C higher than in 2015 and 2011, respectively. New Delhi's average HI was 30.60°C in 2019 and 29.60°C in 2015 (Figure 3). Only 58h in 2015 had HI in the danger level, which increased 4.43 times by 2019 (257h). The high number of hours in danger level of heat stress (and its effect on people according to Table 1) makes it essential to explore design and material solutions to reduce the impact of high outdoor temperature on the indoor operative temperature.

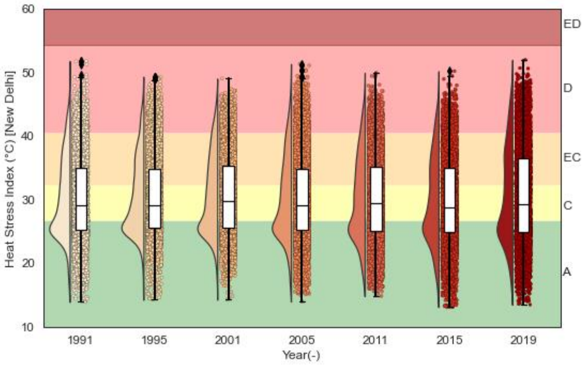

Figure 3: Heat Index (HI) for New Delhi, India, in 1991, 1995, 2001, 2005, 2011, 2015, and 2019. Here, ED= Extreme Danger, D= Danger, EC= Extreme Caution, C= Caution, and A= Acceptable.

Indoor operative temperature: Annual

We simulated the four scenarios under high heat stress conditions (Table 3). The annual simulation showed improved indoor operative temperature compared to the base case. Annually, the average outdoor temperature was 24.81°C, where maximum and minimum were 38.55°C and 6.54°C, respectively. Under the base case scenario, the average annual indoor operative temperature was 37.39°C, where the maximum and minimum were 44.39°C and 23.05°C, respectively (Figure 4). The Jaali reduced the average indoor operative temperature to 31.20°C under the SJ scenario and 31.74°C under the Bio-jaali 1 scenario. After increasing the Jaali thickness under Bio-jaali 2 scenario, the average indoor temperature was increased to 32.05°C. Although the change in Jaali material from Sandstone to mycelium had only a 0.54°C difference (an increase of 1.7%) in average indoor operative temperature annually, a 150% thickness increase in Bio-jaali 2 increased by 0.85°C (+2.7%).

During the summer (April-September), the average outdoor temperature was 30.64°C; the maximum and minimum were 38.55°C and 21.85°C, respectively. The annual average indoor operative temperature was 39.41°C, reduced to 35.83°C, 36.64°C and 37.09°C under SJ, Bio-jaali 1 and 2 scenarios, respectively. However, during the winter (October-March), the average outdoor temperature was 18.94°C; the maximum and minimum were 28.48°C and 6.54°C, respectively. The annual average indoor operative temperature was 35.34°C, reduced to 26.53°C, 26.81°C and 26.97°C under SJ, Bio-jaali 1 and 2 scenarios, respectively. The results showed that the Bio-jaali performed similarly to Sandstone jaali in reducing the (daytime) average indoor operative temperature during summer and keeping most of the days in winter within the acceptable thermal comfort range (19.6-28.5 °C) suggested by IMAC. But this analysis did not reflect on the hourly impact of the Bio-jaali on the indoor temperature. Therefore, we analysed the effect of the Jaali scenarios on hourly indoor temperature during three selected summer and three winter days in the following sections for a detailed understanding.

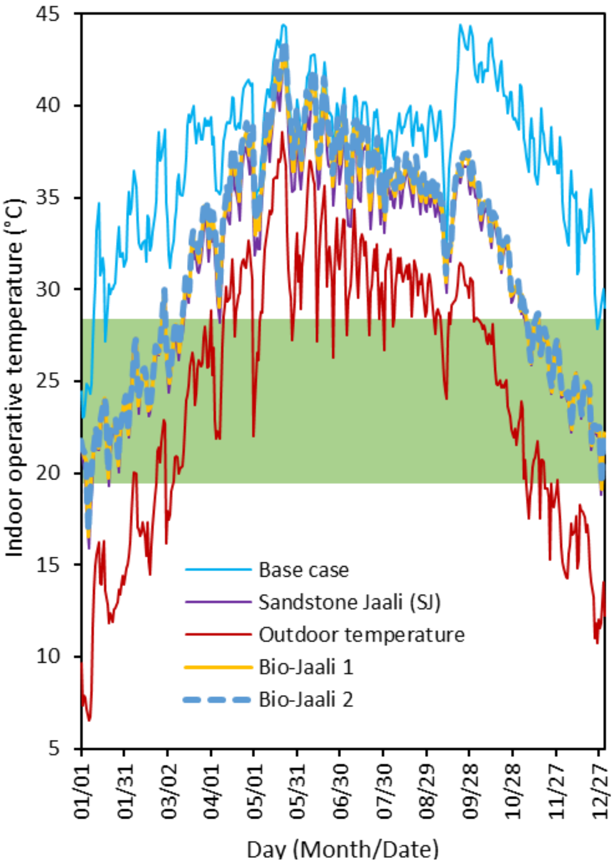

Figure 4:Daily outdoor and indoor operative temperature under the base case, SJ, Bio-jaali 1 and 2 scenarios.

Indoor operative temperature: Summer days

On 1 April, representing the starting period of summer, the average hourly outdoor temperature was 28.84°C, where the maximum was 34.88°C in the afternoon, and the minimum was 23.90°C at night (Figure 5). Under outdoor conditions, the base case scenario's average hourly indoor operative temperature was 39.40°C, reduced under SJ to 33.25°C. The indoor temperature was decreased to 33.88°C and 34.28°C under Bio-jaali 1 and 2, respectively. Therefore, the average hourly indoor operative temperature decreased by 5.12-6.15°C under SJ, Bio-jaali 1 and 2, compared to the base case, especially during the daytime.

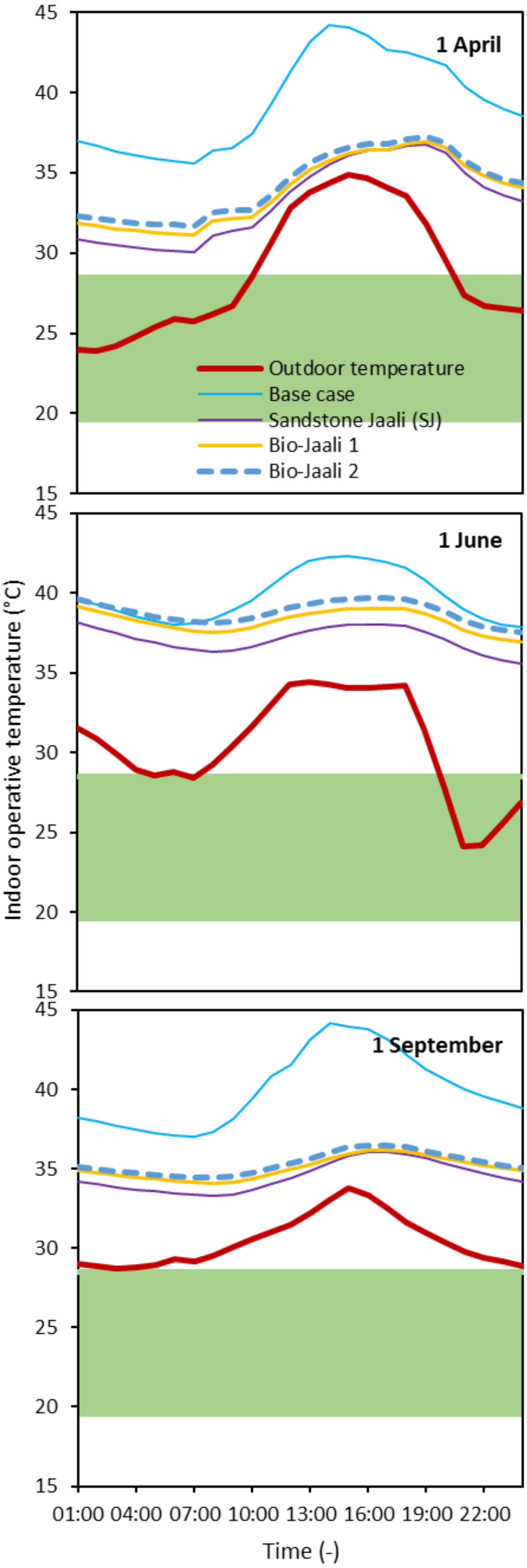

Figure 5: Outdoor and indoor operative temperature under the base case, SJ, Bio-jaali 1 and 2 scenarios, on summer days (1 April, 1 June, and 1 September).

The green area was the acceptable (IMAC) thermal comfort temperature range.

Similar results were simulated on 1 September, representing the end period of summer; the average hourly outdoor temperature was 30.43°C, where the maximum was 33.80°C in the afternoon and the minimum was 28.73°C at night. Under the base case scenario, the average indoor operative temperature was 39.99°C, which was reduced to 34.51°C, 35.05°C, and 35.33°C, respectively, under SJ, Bio-jaali 1 and 2.

However, on 1 June, representing the peak and mid-period of summer, the average hourly outdoor temperature was 30.43°C, where the maximum was 34.45°C in the afternoon, and the minimum was 24.13°C at night. The Bio-jaali reduced the average indoor operative temperature from 39.81°C (Base case) to 38.24°C and 38.81°C under Bio-jaali 1 and 2 scenarios. Although the indoor operative temperature was reduced with SJ and Bio-jaali, the indoor temperature was never within an acceptable thermal comfort range on the summer days suggested by IMAC.

Indoor operative temperature: Winter days

In the case of winter, on 1 November, representing the starting period of the winter season, the average hourly outdoor temperature was 22.72°C, where the maximum was 31.00°C in the afternoon, and the minimum was 17.00°C at night (Figure 6). The base case scenario's average hourly indoor operative temperature was 38.68°C, reduced to 30.21°C, 30.31°C and 30.45°C under SJ, Bio-jaali 1 and 2, respectively. Therefore, the indoor temperature decreased significantly compared to the outdoor base case and stayed within the acceptable thermal comfort range only under Bio-jaali scenarios at night.

On 1 January, representing the peak and mid-period of winter, the average hourly outdoor temperature dropped to 9.64°C, where the maximum was 13.98°C in the afternoon and the minimum was 6.15°C at night; the Bio-jaali reduced the average indoor operative temperature from 24.45°C (Base case) to 21.72°C and 21.79°C under Bio-jaali 1 and 2 scenarios (Figure 6). Although under the SJ scenario, the indoor temperature exceeded 1.16°C more than the acceptable thermal comfort range in the early morning, with Bio-jaali, the temperature was only 0.25°C lower than acceptable limits.

Moreover, on 1 March, representing the end period of winter, the average hourly outdoor temperature dropped to 16.16°C, where the maximum was 21.23°C in the afternoon, and the minimum was 12.35°C at night. Under the base case scenario, the average indoor operative temperature was 34.69°C, which was reduced to 27.12°C, 27.50°C, and 27.70°C, respectively, under SJ, Bio-jaali 1 and 2 scenarios. Under the SJ and Bio-jaali scenario, the indoor temperature stayed within acceptable limits most of the hours of the day.

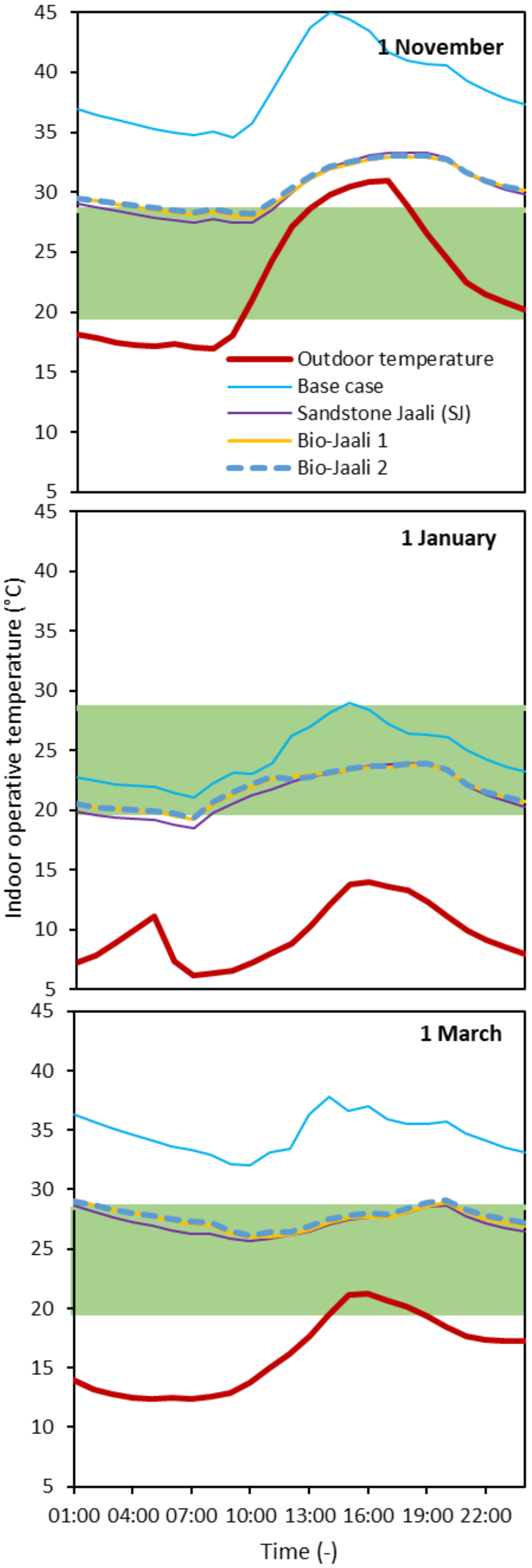

Figure 6: Outdoor and indoor operative temperature under the base case, SJ, Bio-jaali 1 and 2 scenarios, on winter days (1 November, 1 January, and 1 March). The green area was the acceptable (IMAC) thermal comfort temperature range.

https://doi.org/10.26868/25222708.2023.1516

Discussion

The simulation results showed SJ reduced 5.22% of the annual average indoor operative temperature, whereas Bio-jaali were able to reduce 1.86-3.04% than the base case. The SJ reduced the daily average indoor operative temperatures by 6.82-15.60% and 12.74-22.14% in summer and winter, respectively, compared to the base case scenario. However, the results showed a 3.95-14.01% and 11.17-21.64% reduction in daily average indoor operative temperatures with Bio-jaali 1 (with the same thickness of SJ scenario) compared to the base case during the summer and winter, respectively. Highly likely due to the insulation capabilities of the mycelium material (Jones, et al., 2020). Furthermore, the perforations on the Bio-jaali also allowed natural ventilation, efficiently making it suitable for extreme heat and winter scenarios. Under the Bio-jaali 2 scenario, the thickness was increased (150% from 0.04m in Bio-jaali 1) to analyse the effect of the increased thickness of Bio-jaali on the indoor temperature. The results showed that Bio-jaali 2 increased the indoor operative temperature from 0.71-1.44% and 0.30-0.56% in summer and winter, respectively, compared to Bio-jaali 1, indicating the effect of increased thickness of mycelium in Bio-jaali. This study aimed to explore the potential of mycelium as the construction material for replacing traditional sandstone for Jaali. The results show that mycelium could be a potential material for replacing sandstone. However, further research would be required to explore and increase its impact on reducing indoor temperature and associated cooling load.

Figure 7: Bio-fabricated 160mm X 160mm Bio-jaali prototype panel with circular aperture

The Bio-jaali were air permeable with their insulation capabilities. As made of mycelium composites, airflow, insulating properties, and high albedo would cool down the incoming air, reducing the cooling demand. 'Bio-jaali' would have high fire resistance, be carbon negative (Livne, et al., 2022) and be low in weight and cost as the mycelium composites would be made from agriculture waste such as sawdust, wheat, and rice straw, which might assist in reducing stubble burning: one of the significant causes of air pollution in New Delhi, India. Bio-jaali would reduce material wastage, dead load on the building structure, and embodied carbon (Livne, et al., 2022) associated with commonly used materials (bricks and stones).

Our preliminary bio-fabricated mycelium composites and prototype panel (Figure 7) showed hydrophilic capabilities under high relative humidity conditions, which was also evident in other studies where mycelium composites showed ~40–580 wt% moisture uptake higher than those of polystyrene (0.03–9 wt%) and polyurethane (0.01–72 wt%) (Jones, et al., 2020). The hydrophilic characteristics were a limitation as they made the composite decompose fast. As the perforated screen would be bio-fabricated, various patterns can be adopted to increase the airflow with very low weight. Furthermore, Bio-jaali would also utilise the static humidity-responsive capabilities of mycelium composites to cool the incoming air into indoor spaces.

The simulated results from the scenario-based analysis would assist in developing a new generation of low-cost, low-environmental impact, responsive building skins that moderate internal temperature and humidity by varying their porosity for the 'RESPIRE: Passive, Responsive, Variable Porosity Building Skins' project. The building-level application of mycelium materials was almost non-existent due to high water absorption characteristics and limited mechanical properties, mainly compressive strength (Jones, et al., 2020). This study was an initial step towards understanding the viability and potential of mycelium materials as building skin, which would inform further studies in developing low-cost, low-environmental impact, mycelium-based building skins.

Conclusion

Climate change-induced global warming and frequent extreme heat events elevated the heat stress level in Megacities such as New Delhi, India, which fulled the elevated ownership and use of active cooling. To reduce the dependency on active cooling, in this study, we aimed to re-design 'Jaali'— perforated screens made of bricks and sandstones to cool the incoming air inspired by historical building use— with bio-based materials such as mycelium. We conducted a climate analysis and performance-based dynamic building physics simulation in a single-zone indoor office space, which proved our hypothesis that 'Bio-jaali' would reduce indoor operating temperature passively. The simulation results showed Sandstone Jaali decreased by 5.22% of the annual average indoor operative temperature, whereas Bio-jaali were able to reduce by 3.04% than the base case. Our simulation also demonstrated 3.95-14.01% and 11.17-21.64% reductions in daily average indoor operative temperatures with Bio-jaali compared to the base case during the summer and winter, respectively.

Furthermore, the seasonal analysis showed that Bio-jaali reduced the summer indoor operating temperature by decreasing heat gain from outdoor heat during the daytime and increased indoor temperature during winter by reducing heat loss, demonstrating its potential for year-round usage. Although limitations of the mycelium materials, such as high hydrophilic and low mechanical properties, may require further research for exterior use, this study was an initial step towards demonstrating the viability and potential of mycelium-based building applications. Furthermore, this study would inform ongoing and further studies in developing low-cost, low-environmental impact building skin.

Acknowledgement

This research was funded by the ‘RESPIRE: Passive, Responsive, Variable Porosity Building Skins’ project (ID/Ref: 91782) funded by Leverhulme Trust. We want to thank Meteoblue (www.meteoblue.com) for the climate data collaboration.

References

Al-janabi, A., Kavgic, M., Mohammadzadeh, A. & Azzouz, A., 2019. Comparison of EnergyPlus and IES to model a complex university building using three scenarios: Free-floating, ideal air load system, and detailed. *Journal of Building Engineering,* Volume 22, pp. 262-280.

Choi, G. & Lee, D. E., 2020. Changing human-sensible temperature in Korea under a warmer monsoon climate over the last 100 years. *International Journal of Biometeorology,* pp. 1-10.

Debnath, K. B. & Jenkins, D. P., 2020. *Simulation-based assessment of residential energy demand reduction strategies for cooling in a south Indian community.* Loughborough, IBPSA England.

Debnath, K. B., Jenkins, D. P., Patidar, S. & Peacock, A. D., 2020. Understanding residential occupant cooling behaviour through electricity consumption in warm-humid climate. *Buildings,* 10(4), p. 78.

Debnath, K. et al., 2022. *Climate Change and Megacities: South Asian Megacities are in extreme heat stress.* Santiago, Chile, 36th PLEA Conference 2022: Sustainable Architecture and Urban Design, pp. 1009-1014.

Fay, T. H. & Hardie, K. A., 2003. Fahrenheit to Celsius: An exploration in college algebra. *Mathematics and Computer Education,* 37(2), pp. 207-209.

GoI, 2015. *India Energy Security Scenarios 2047.* [Online] Available at: http://iess2047.gov.in

Huang, S. & Wu, D., 2019. Validation on aggregate flexibility from residential air conditioning systems for building-to-grid integration. *Energy and Buildings,* Volume 200, pp. 58-67.

IEA, 2019. *Energy Efficiency: Cooling.* [Online] Available at: https://www.iea.org/topics/energyefficiency/buildings/cooling/
[Accessed 21 March 2022].

IPCC, 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability,* s.l.: Cambridge University Press.

Jones, M. et al., 2020. Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Materials & Design,* Volume 187, p. 108397.

Livne, A., Wösten, H. A., Pearlmutter, D. & Gal, E., 2022. Fungal mycelium bio-composite acts as a CO2-sink building material with low embodied energy. *ACS Sustainable Chemistry & Engineering,* 10(37), pp. 12099-12106.

Luo, M. & Lau, N.-C., 2019. Characteristics of summer heat stress in China during 1979--2014: climatology and long-term trends. *Climate Dynamics,* 53(9-10), pp. 5375-5388.

Manu, S. et al., 2016. Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC). *Building and Environment,* Volume 98, pp. 55-70.

Modarres, R., Ghadami, M., Naderi, S. & Naderi, M., 2018. Future heat stress arising from climate change on Iran’s population health. *International journal of biometeorology,* 62(7), pp. 1275-1281.

NIH, 2022. *Effects of Heat.* [Online] Available at: https://www.niehs.nih.gov/research/programs/climatechange/health_impacts/heat/index.cfm#:~:text=Prolonged%20exposure%20to%20extreme%20heat,%2C%20cerebral%2C%20and%20cardiovascular%20diseases.
[Accessed 21 March 2022].

NWS, 2020. *What is Heat Index?.* [Online] Available at: https://www.weather.gov/ama/heatindex
[Accessed 2020].

Opitz-Stapleton, S. et al., 2016. Heat index trends and climate change implications for occupational heat exposure in Da Nang, Vietnam. *Climate Services,* Volume 2, pp. 41-51.

Prasad, R. et al., 2022. Jaali a tool of sustainable architectural practice: Understanding the feasibility and usage. *Materials Today: Proceedings,* Volume 60, pp. 513-525.

Rothfusz, L. P. & Headquarters, N. S. R., 1990. *The heat index equation (or, more than you ever wanted to know about heat index),* Fort Worth, Texas: National Oceanic and Atmospheric Administration, National Weather Service, Office of Meteorology.

UN, 2018. *The World’s Cities in 2018—Data Booklet,* s.l.: United Nations.

Xu, X., Taylor, J. E. & Pisello, A. L., 2014. Network synergy effect: Establishing a synergy between building network and peer network energy conservation effects. *Energy and Buildings*, Volume 68, pp. 312-320.

Yoon, J. H., Baldick, R. & Novoselac, A., 2014. Dynamic demand response controller based on real-time retail price for residential buildings. *IEEE Transactions on Smart Grid,* pp. 121-129.

Zhang, X., Hu, J., Fan, X. & Yu, X., 2022. Naturally grown mycelium-composite as sustainable building insulation materials. *Journal of Cleaner Production,* Volume 342, p. 130784.