



# Occupant Thermal Comfort versus Poor Air Quality of Wooden Houses in the Highlands

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**Abstract:** Humans need a comfortable and healthy home to carry out activities properly. Low-income people's homes in the Highlands have poor indoor air quality due to stoves that produce smoke. People also use stoves as a heating tool to achieve thermal comfort. This study aimed to investigate thermal comfort and poor air quality in Wooden Homes in the Highlands. The study used a mixed method. Qualitative methods were used to obtain data on the thermal comfort of occupants. Quantitative methods were used to obtain data on indoor air quality. The study results showed opposing aspects between thermal comfort in people in the highlands and the fulfillment of clean and healthy air. The study also created solutions for thermal comfort and clean air quality by simulating ventilation placement.

**Keywords:** architecture; cold; comfort; indoor air quality; occupant

## 1 INTRODUCTION

Energy waste is still an essential issue in all scientific fields. Science must be integrated to find solutions to energy problems. Zero-energy buildings are one solution to reducing energy waste [1]. Various simulations of buildings to create energy-free buildings are carried out using various methods [2].

Investigations into building types have also been carried out. One type of building that is thought to create thermal comfort for its occupants is a vernacular building [3]. Wooden houses are one of the vernacular mountain houses in Indonesia that have local wisdom in using fireplace [4]. Wooden houses are sustainable houses that use environmentally friendly materials [5].

The culture of heating with traditional stoves in highland houses creates a concept of kinship that makes it comfortable for its occupants. The community is also thermally comfortable with heating using traditional fire stoves. Fire stoves produce smoke that can cause health problems for residents. Traditional fire stoves are used by low-income people who are forced to use fire stoves for cooking [6].

Thermal comfort is the user's perception of the environment they live in. Perception is based on the ASHRAE thermal sensation scale [7]. Climate variables in thermal comfort are air temperature, main radiant temperature, air humidity, and wind speed [8]. Clothing and activities are personal thermal comfort variables that also affect the thermal comfort of building occupants.

Temperature is one of the climate variables always included in the discussion of thermal comfort and building thermal performance [9]. The discussion of air humidity is one set with the discussion of temperature because the two variables are closely related [10]. Discussion of the two variables in assessing the thermal performance of buildings is something that cannot be left out and is an integral part of assessing the thermal performance of buildings [11].

Discussions of thermal comfort can be done using the Predicted Mean Vote (PMV) theory. The PMV parameter is still used even though some researchers consider it lacking [12]. PMV is known as an expanded and flexible theory of

thermal comfort. The difference between PMV and Actual Mean Vote (AMV) makes researchers compare the two aspects in many research objects [13].

Discussion of thermal comfort can also be seen using Actual Mean Vote (AMV). Thermal comfort assessment with AMV can create a thermal comfort prediction model [14]. Operative temperature is one of the variables discussed in AMV. Operative temperature is obtained from the average air temperature and average solar radiation temperature [15].

Thermal comfort in vernacular houses is attractive to discuss with the local wisdom found in vernacular houses. Research on thermal comfort in vernacular houses requires higher accuracy because researchers must apply quantitative and qualitative methods to obtain comprehensive results [16].

The indoor environment can be monitored by measuring temperature, humidity, and particulate matter [17]. Measurements are made in outdoor and indoor spaces whose results can be compared so that differences in air content are found in outdoor and indoor spaces [18]. The interior space can be measured from several types of space. The interior space that has a large particulate matter (PM) value is the kitchen [19]. Indoor space can be measured from several types of spaces. Kitchens have a sizeable particulate matter (PM) value [20].

One variable in thermal comfort is wind speed. The content of substances in the air can affect the thermal comfort of occupants and the air quality in the room [21]. Particulate matter (PM) can be seen from measurements, including PM1, PM2.5, and PM10 [22]. Investigations of room air quality more often measure particulate matter using PM2.5 [23].

Temperature and PM2.5 measurements are also a reference in determining the criteria for sick building syndrome [24]. Temperature is related to indoor air quality, measured based on PM2.5 content. Both variables are essential things that affect the comfort and health of building occupants.

Research into indoor air quality in wooden houses under similar conditions in the European Union is characterized, for example, by the works mentioned below. Research in Spain discusses historical buildings that are considered to have local wisdom such as wooden houses. Poor indoor air quality

can be improved by retrofitting [36]. Research on wooden houses in Denmark that discusses the positive aspects of the sustainability of wooden houses [37]. Indoor Air Quality has not been discussed comprehensively in this research. Research in Chile discusses the presence of air pollution in wooden houses when firewood is used by low-income communities [38]. The research discusses particulate matter (PM) 2.5 and has not discussed other PM. Another article does not discuss indoor air quality of wooden houses specifically but discusses the development of wooden house fabrication which is included in bio-based materials. Residential houses in Central and Eastern Europe are suitable for developing bio-based material fabrication, one of which is wooden houses [39].

Scientific developments that discuss indoor air quality have been widely carried out using particulate matter content variables. However, discussions of poor air quality juxtaposed with users' thermal comfort have not been widely carried out. Comparisons of the thermal comfort of residential residents based on the highlands' heating culture have also not been discussed from an architectural or scientific perspective. The novelty of the research is the discussion of the study of the culture of heating with poor air quality so that solutions will be found to maintain the culture and solve the problem of poor air quality in the highlands. The results of the research will have a broad impact on society in terms of maintaining local wisdom and creating healthy homes. The solutions provided will impact the community's happiness because they will create health and comfort. The purpose of the research is to investigate the air quality inside wooden residential houses associated with the highlands' heating culture. The research will provide a strategy for creating good air quality without eliminating the existing culture.

## 2 METHODS

The study used a mixed method. Data was collected through observations, interviews, and measurements in the field.

### 2.1 Research Object

The study was conducted on one hundred wooden-walled houses using traditional stoves (Fig. 1). The floor of the building uses concrete and soil materials. The roof uses zinc. The building is not too big, ranging from 21 to 45 m<sup>2</sup>. The ventilation of the house tends to be closed because of the cold climate in the highlands.

### 2.2 Data Collection

Observation collected data to obtain data on residential house images consisting of room plans, elevations, and perspective images. Photos of residential houses were taken to complete the results of more detailed residential house images. Interviews were conducted to determine the thermal comfort felt by the residents of the house and the activities of the residents. Air temperature, humidity, and particulate

matter (PM<sub>2.5</sub>) data were measured using a thermal measuring device, and indoor air quality was assessed. Measurements were carried out every a quarter of an hour in one day starting from 06.00-21.00 western Indonesia time.



Figure 1 Research Object 100 wooden houses

## 3 RESULTS AND DISCUSSION

### 3.1 "Geni" culture using traditional fire stoves

The highlands in Wonosobo Regency have a cold climate, so people need heating. The lower middle class uses traditional fire stoves to heat their homes. Most low-income people work as farm laborers and have wooden houses. The heating process using traditional fire stoves has been carried out since ancient times and still persists today.

The heating process has become a culture of gathering for highland people. Several areas in Wonosobo Regency call the culture of gathering by lighting a fire the "geni" culture. Several other areas call it the "genen" culture. The "geni" culture is a place to gather while warming up. The "geni" culture, initially only intended for warming up, has changed into a social need for the community.

The "geni" culture is a place to discuss everything from informal to formal. Informal discussions include daily activities related to agriculture, personal problems related to family life, and social relations problems. Formal discussions, such as hamlet or village-level meetings, are also sometimes discussed while warming up with a traditional fire stove.

Observation results from 100 wooden houses that use traditional fire stoves show that the traditional fire stove functions primarily as a heating tool, while cooking is an additional function. The traditional fire stove is used to cook rice without using a magic jar. People often use the magic jar to cook rice because it cooks faster. The traditional fire stove is used more to boil water to make coffee. For people who cannot afford to buy a magic jar, they will use the traditional fire stove as the main cooking tool.

The traditional fire stove is placed in the kitchen with a small table and chairs. A small table known as "dingklik" is

used to put drinks and snacks. A small chair known as "jengkok" is used for residents of the house or guests who visit the house to chat. People call chatting "ngendhong".

Several chairs in the kitchen are used as "ngendhong" facilities.

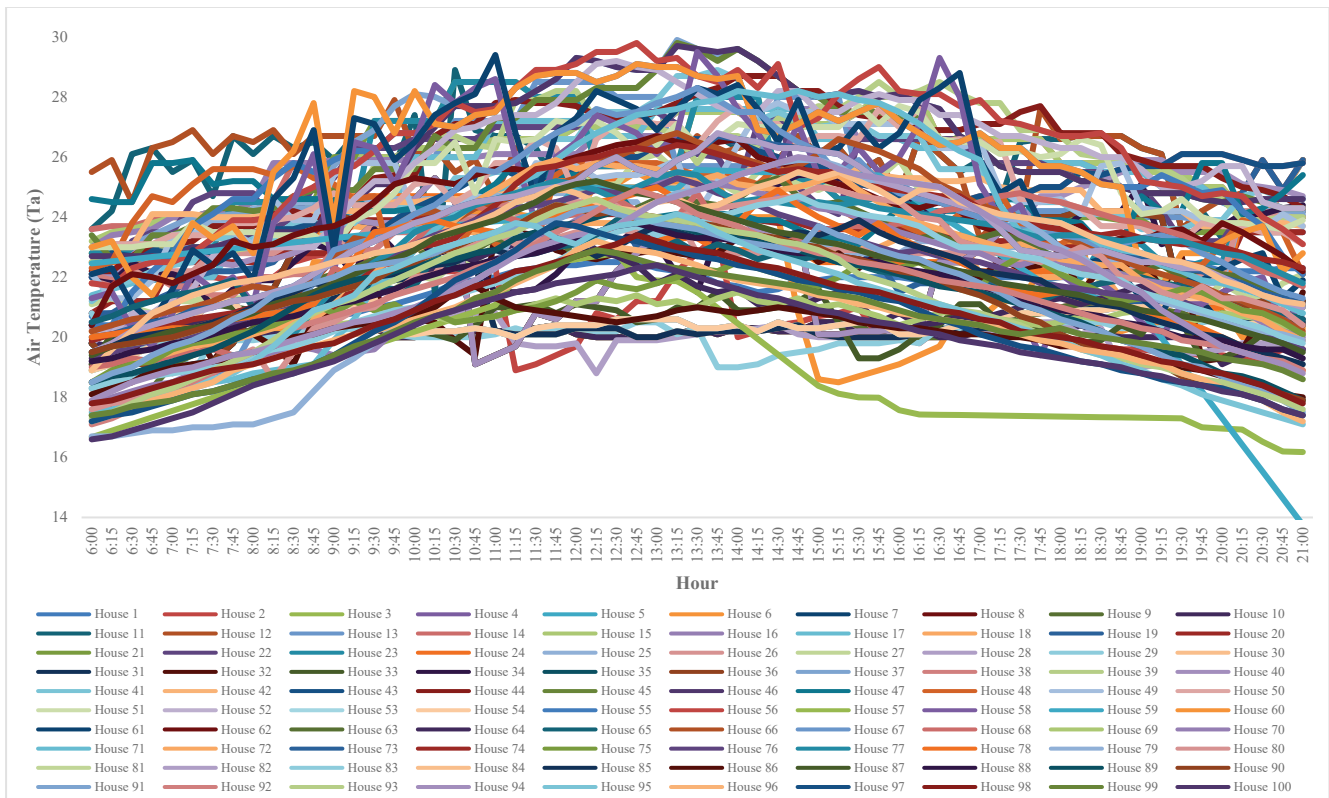


Figure 2 Indoor Temperature

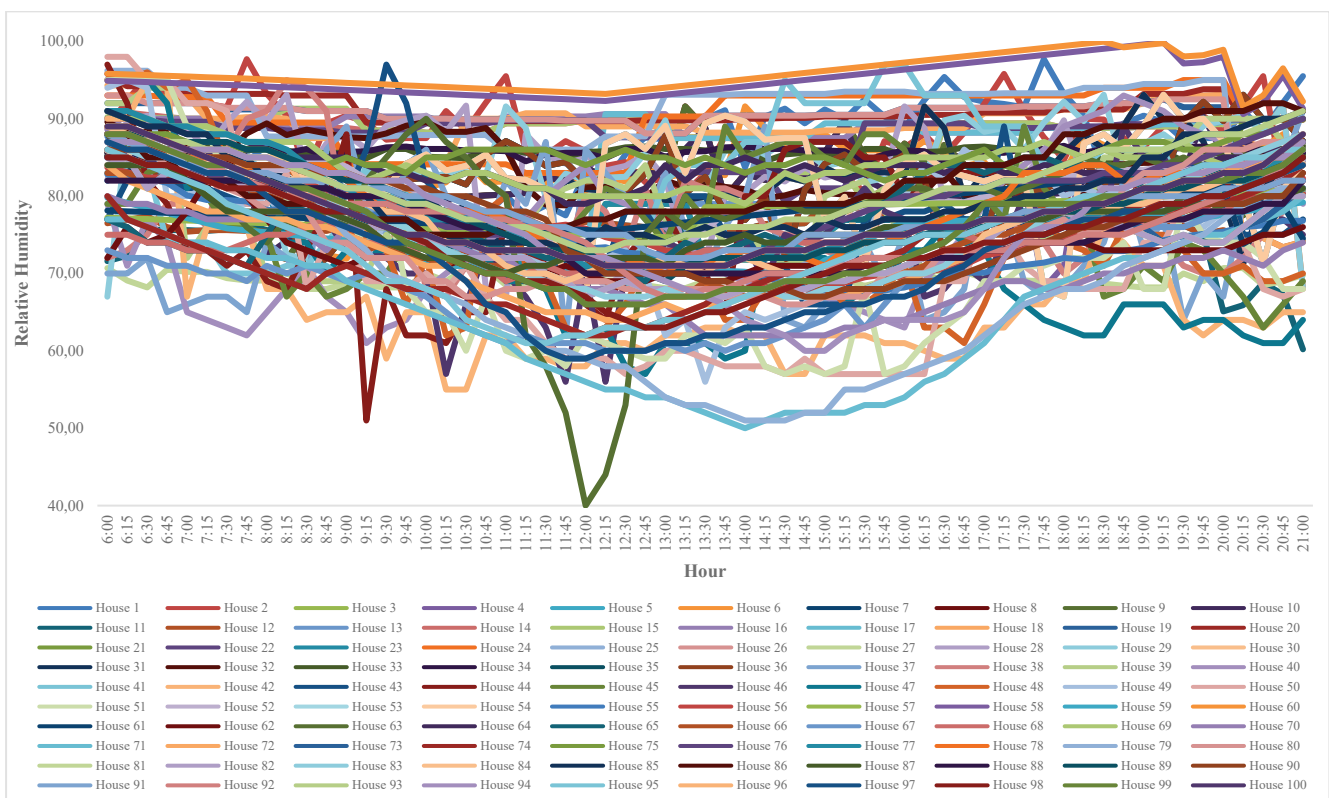


Figure 3 Indoor Relative Humidity

Interview results from residents of the house explained that residents feel warm and comfortable when they are in the kitchen. The occupants feel calm, comfortable, and peaceful in the presence of a burning stove. The occupants feel calm in the presence of a burning stove because it indicates that the occupants have food that can be eaten. The feeling of comfort arises with the warming process due to the stove's heat. The feeling of peace from the occupants occurs due to the harmony with routine socializing. Problems can be resolved when gathering in the kitchen by lighting the stove.

### 3.2 Air Temperature and Humidity

One hundred houses have similar air temperatures. The lowest air temperature of 13.75 °C was obtained from house 59 at 21.00 (western Indonesia time). The highest air temperature of 29.90 °C was obtained from house 37 at 13.15 (western Indonesia time). The average air temperature of one hundred houses is 22.86 °C (Fig. 2). Comfortable air temperatures in mountainous areas are around 24 °C, indicating that people should still feel cold with indoor air temperatures below mountain communities' comfortable temperature [25]. People feel comfortable with the presence of a fire pit as a heating device, coupled with a feeling of calm and serenity, making the cold air temperature not too felt by the house's occupants.

The humidity between one wooden house and another shows similar results. The lowest humidity of 40% was obtained from house 63 at 12.00 (western Indonesia time). The highest humidity of 99.96% was obtained from house 60 at 18.30 (western Indonesia time) (Fig. 3). House 63 more often uses traditional stoves, thus reducing the water content in the room. Using stoves that produce smoke will make the air in the home environment drier, resulting in the lowest humidity. House 60 shows wet conditions with the floor still made of soil. The water in the soil floor is higher than other floor materials. The vegetation around house 60 is quite a lot and will produce water vapor, thus making the surrounding humidity high.

### 3.3 Particulate Matter (PM2.5)

Traditional stoves will produce smoke in the kitchen (Fig. 4a). The distribution of smoke in each house is different, but most of the smoke cannot escape smoothly because ventilation is not available properly. Some houses have kitchens with minimal ventilation so that the spread of smoke reaches the family room and living room (Fig. 4b). Highland communities cannot eliminate traditional stoves with the "geni" culture, which is believed to create harmony within the community. In addition, low-income communities consider stoves to be cheaper than gas stoves. People can get wood fuel for stoves from the forest. Taking wood for fuel is known by the community as "repek".

Particulate matter in wooden houses with stoves can be caused by several aspects, such as dust pollution from wooden wall materials, smoke produced by the stove, and dust from the dirt floor used. Smoke from traditional stoves

significantly increases PM2.5 values (Fig. 5). Other smoke comes from motorcycle exhausts placed in the living room.



Figure 4 a) Smoke is coming out of the stove; b) Lack of ventilation in the kitchen

The highest value of particulate matter (PM2.5) in the research object occurred in house 63 at 14.00 (western Indonesia time) at 426  $\mu\text{grams}/\text{m}^3$ . A very high value for PM2.5 occurred in house 63 due to smoke. Traditional stoves in house 63 are more frequent because the occupants do not have other cooking utensils, such as magic jars. The lowest PM2.5 value occurred in house 59 at 12.45 (western Indonesia time) at 0.9  $\mu\text{grams}/\text{m}^3$  because the traditional stove was not used at 12.45 (western Indonesia time). The use of traditional stoves greatly affects the PM2.5 value. The particle content originating from wooden wall materials or dust from dirt floors is insignificant in affecting the PM2.5 value. Low-income people inhabit house 59. The average PM2.5 value from one hundred houses is 62.11  $\mu\text{grams}/\text{m}^3$ . The average value remains higher than the minimum PM2.5 threshold of 40  $\mu\text{gram}/\text{m}^3$ . One hundred wooden houses used as research objects had poor air quality regarding PM2.5 content.

Data analysis of the relationship between PM (Particulate Matter) and temperature using visualization with tecplot software. The relationship between air temperature and PM2.5 in one hundred houses shows graphic variations. Very high PM2.5 values occur in several houses throughout the day, both when the temperature is 18.5 to 24 °C (Fig. 6a). Several other houses show high PM2.5 values when the air temperature is between 19 and 22 °C (Fig. 6b).

The average thermal variables of one hundred houses from 06.00-21.00 can be seen in Fig. 7. Air temperature ( $T_a$ ), mean radiant temperature (MRT) and operative temperature ( $T_o$ ) show similar results. The variable values are between 20 and 30 °C. Relative humidity (RH) is seen between 60-80%. Velocity is closer to still, so the value obtained is not more than 0.1 m/s. Thermal sensation votes (TSV) have more negative values because of the cold climate conditions. PM2.5 (Particulate Matter) content of more than 50  $\mu\text{gram}/\text{m}^3$  is higher than the maximum limit of PM2.5 content required of 40  $\mu\text{gram}/\text{m}^3$ . The clothing and activity variables of the occupants are variables that are taken into account in thermal comfort. Most occupants of buildings in the highlands wear long-sleeved clothes, long pants for men,

and skirts for women. The community also wears a special head covering for men and a jilbab for women. The clothing

value is 0.61. Activities at home are sitting and chatting, which is worth one meeting.

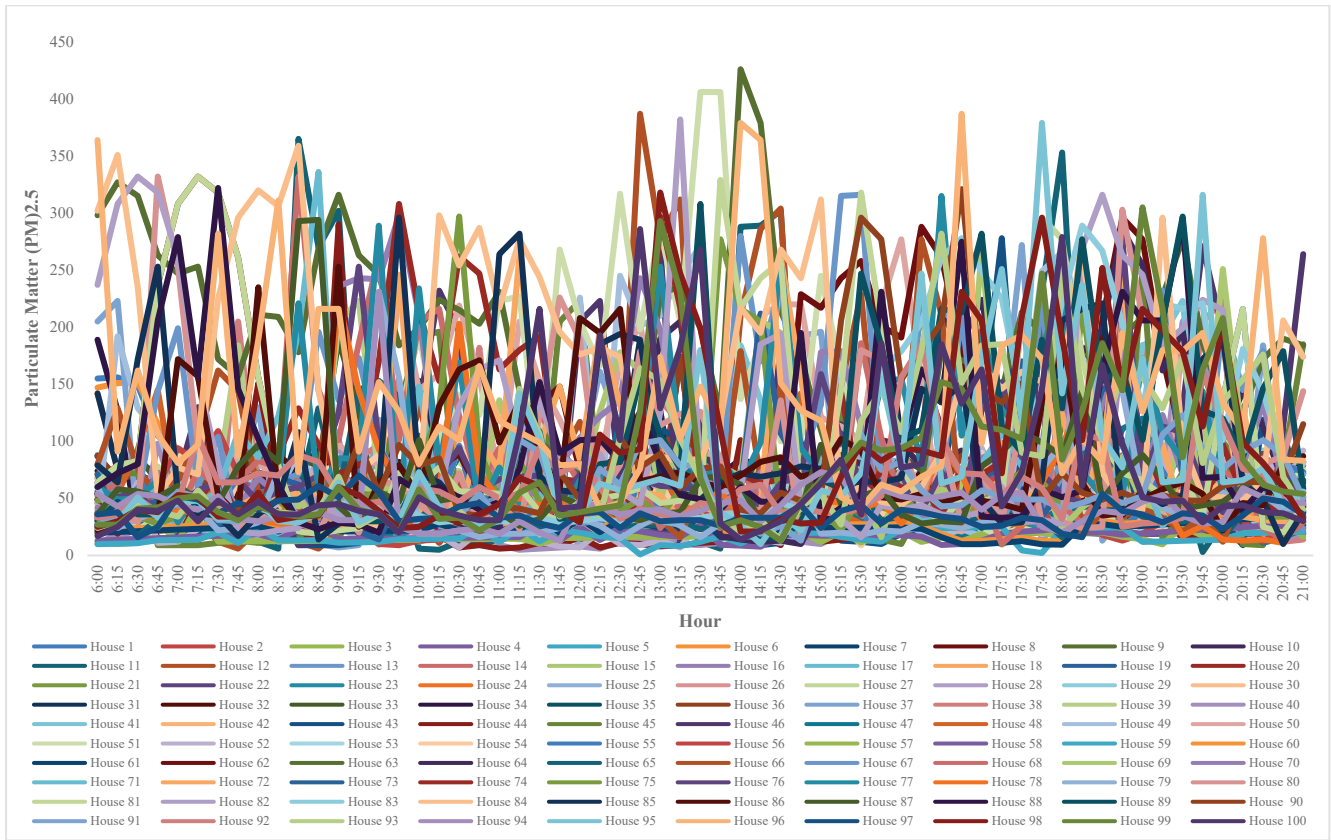


Figure 5 Indoor Particulate Matter

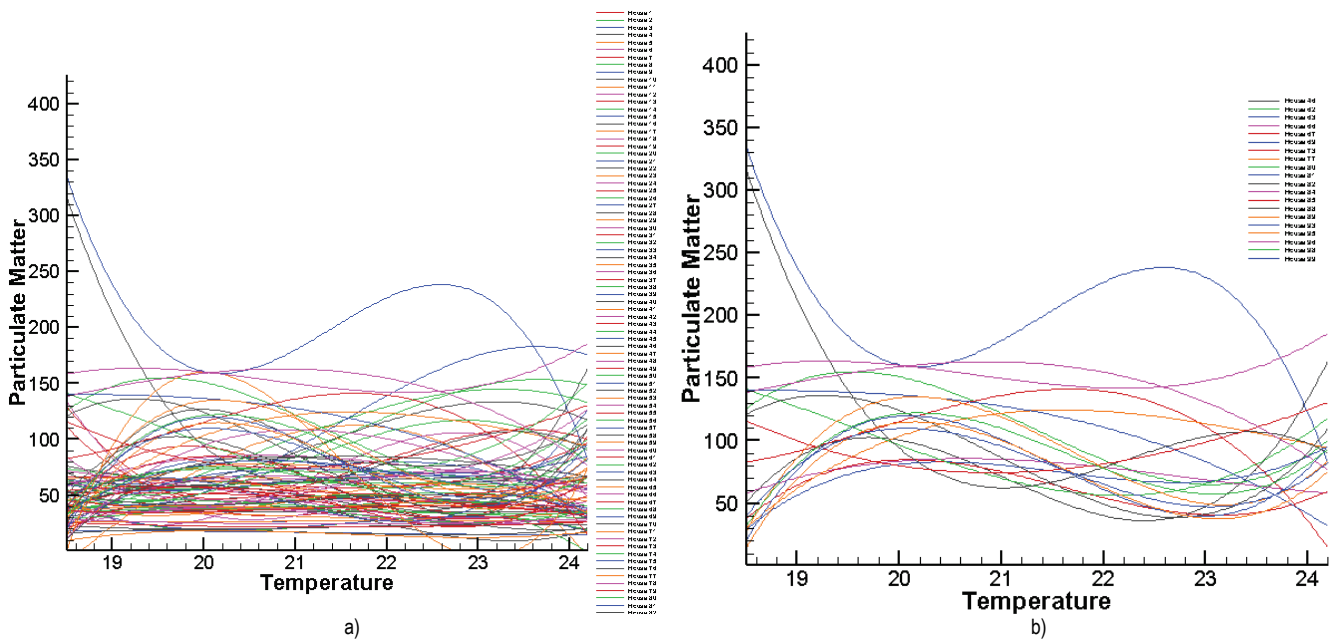
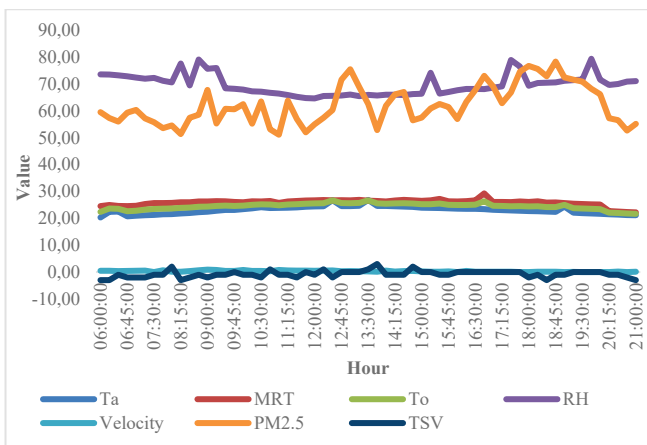


Figure 6 a) Relationship between Temperature and PM2.5 in one hundred houses; b) High PM2.5 content in several houses.

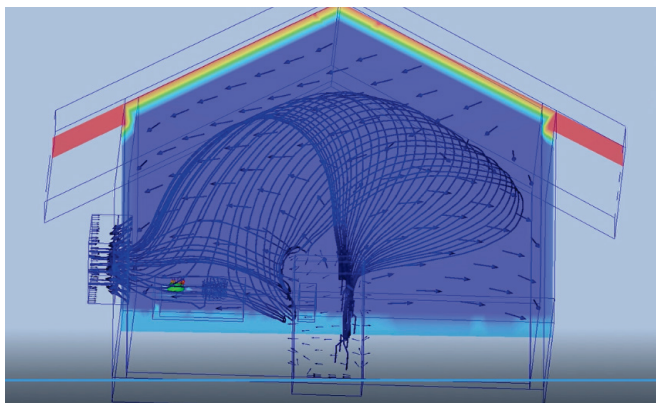


**Figure 7** Average Variable Value (Annotation: Ta = Air Temperature, MRT = Mean Radiant Temperature, To = Operative Temperature, RH = Relative Humidity, PM = Particulate Matter, TSV = Thermal Sensation Vote).

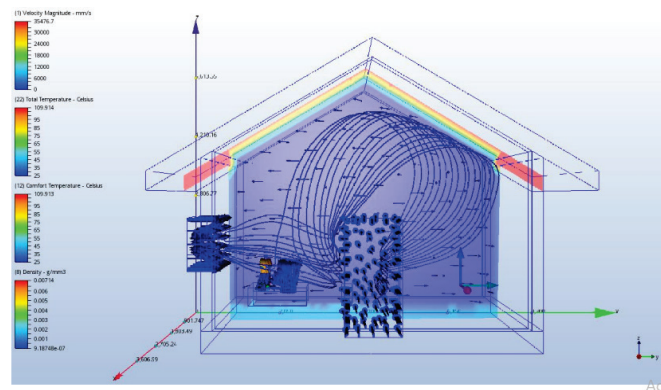
### 3.4 Air Quality Improvement Strategy

Air quality improvement can be improved by improving architectural elements so smoke can exit the room smoothly. Clean air from outside that enters the room can push smoke out of the room properly. Ventilation is one element that needs to be optimized to create healthy and clean air elements. Ventilation in the kitchen can be added by directing smoke outside, but it can still warm the room. Creating an Air Quality Improvement Strategy using Computational Fluid Dynamic (CFD) Revit.

The kitchen of a wooden house has ventilation but is often closed because of the cold climate in the highlands.



a)



b)

**Figure 8** a) Airflow in a room with closed ventilation; b) Airflow out through one open vent

The first alternative solution to overcome smoke is to add a hole in the roof (Fig. 9a). Smoke does not move directly towards the hole in the roof. Some smoke moves around in the room, and some towards the hole in the roof. Roof windows perform better than mechanical ventilation. The roof window needs to be designed in such a way that it can circulate air smoothly [32]. Roof ventilation can also lower the air temperature, creating thermal comfort for users. Airflow from roof ventilation can lower the temperature by 7% [33].

The second alternative is to make a chimney so that the smoke can be directed out through the chimney. Using a

Airflow is not free to escape through closed ventilation (Fig. 8a). Open ventilation will smooth the airflow even though it cannot remove smoke in the room (Fig. 8b). Standard ventilation with a size of around 60×40 cm cannot push smoke out of the room.

Building improvements are needed to create thermal comfort and health for building occupants. The building envelope is one factor that needs to be improved to improve the quality of the building [26]. Designing wooden residential products is one solution to creating sustainable buildings. Wooden houses need to be designed with a modern model so that people are more interested in building those [27].

Ventilation is an architectural element that determines the air exchange in a room. Wooden houses in the highlands use more windows that can be opened. Smoke from traditional stoves will flow towards the window after rotating in the room. Traditional stoves make the exchange of air in the room (Fig. 4). The placement of existing windows needs to be supplemented with other ventilation so that the airflow becomes smoother. The cross-ventilation model will make the airflow move more freely [28]. Effective windows in the kitchen will improve kitchen performance and make the house healthier [6]. The size of the windows in the kitchen needs to be adjusted to the activities in the kitchen so that more outside air enters the kitchen and can replace the hot air produced by the kitchen [29]. Increasing air volume in the room will create thermal comfort for building users [30]. Airflow and thermal comfort can be achieved with the cross-ventilation model. Cross ventilation will create airflow that can bring thermal comfort [31].

chimney to channel smoke out of the house has been recognized as effective. A chimney can use solar energy [34]. The determination of the slope of the chimney needs to be adjusted to the type of activity and airflow in the room [35]. Using chimneys for low-income people is quite difficult because the cost of making chimneys is quite large. The chimney design needs to be simple but highly effective. The design can be made using zinc material from the teer place. Several houses in the highlands owned by low-income people use "blek," a used teer place, as an additional wall. The chimney's slope can affect the smoke exit from inside to outside the room.

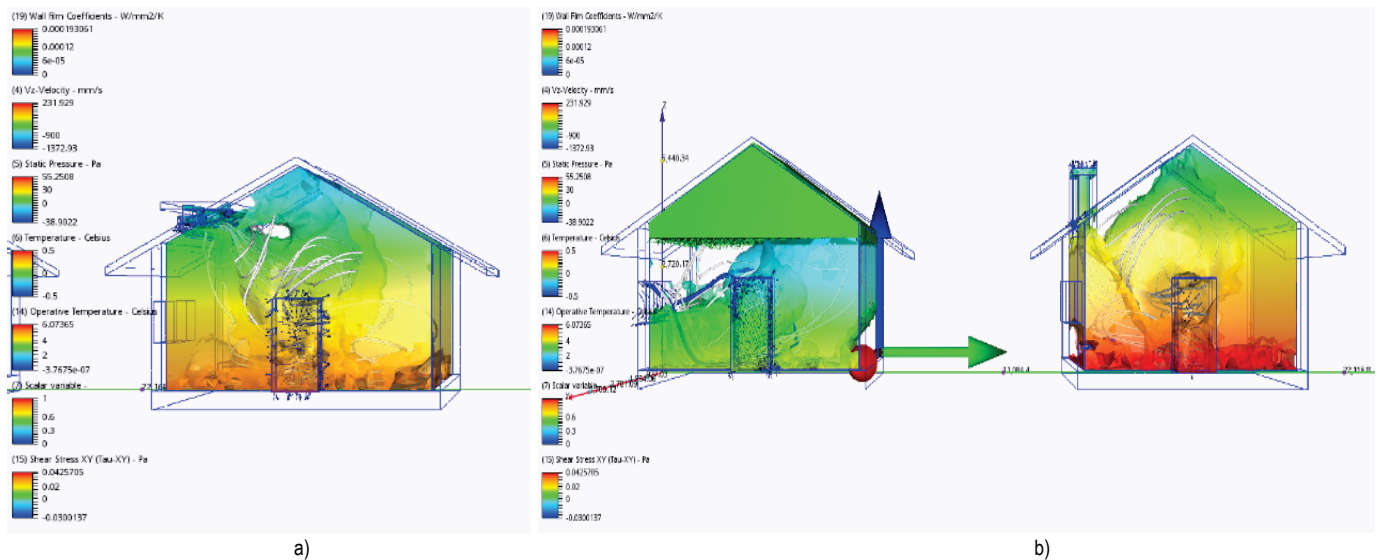


Figure 9 a) Addition of roof ventilation; b) Addition of a roof chimney.

## 4 CONCLUSION

Thermal comfort that is contrary to the fulfillment of health in homes occurs in highland areas. Ventilation is one of the important parts that needs to be created in order to be a solution in creating healthy and energy-efficient homes. The thermal comfort of residents of wooden houses in the highlands is fulfilled by the "geni" culture that the highland community has carried out for generations. Poor air quality occurs in wooden houses with inadequate ventilation, so air cannot circulate properly. The thermal comfort of the occupants that has been met needs to be maintained, and additional ventilation is needed so that airflow is smoother.

The strategy that can be done so that the culture of the occupants can be maintained and good thermal comfort is created by adding building elements to the kitchen. Improper ventilation placement makes the smoke from the fireplace unable to escape smoothly so that the placement and opening of the ventilation need to be modified so that the smoke can escape smoothly. Roof ventilation needs to be made so that some of the smoke can escape through the roof hole. The chimney needs to be made with a placement close to the center of the smoke so that the smoke can exit the room directly. The recommendation for further research is a strategy for creating thermal comfort that can be connected to sensors so that automation is created to create thermal comfort without eliminating the culture that has developed in society.

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## 5 REFERENCES

- [1] Ahmed, K., Hasu, T., & Kurnitski, J. (2022). Actual energy performance and indoor climate in Finnish NZEB daycare and school buildings. *Journal of Building Engineering*, 56, 104759. <https://doi.org/10.1016/j.jobee.2022.104759>
- [2] Izadyar, N., & Miller, W. (2022). Ventilation strategies and design impacts on indoor airborne transmission: A review. *Building and Environment*, 218, 109158. <https://doi.org/10.1016/j.buildenv.2022.109158>
- [3] Wang, F., Wang, S., Cheng, B., & Wang, W. (2022). To inhabit, retain or abandon? Adaptive utilization of energy-efficient sunken buildings by rural households in Shanzhou, China. *Energy and Buildings*, 255, 111668. <https://doi.org/10.1016/j.enbuild.2021.111668>
- [4] Hermawan, Prijotomo, J., & Dwisusanto, Y. B. (2020). The Geni tradition as the center of the shelter for Plateau Settlements. *Ecology, Environment and Conservation*, 26(1), 34-38.
- [5] Al Tawayha, F., Braganca, L., & Mateus, R. (2019). Contribution of the vernacular architecture to the sustainability: A comparative study between the contemporary areas and the old quarter of a Mediterranean city. *Sustainability*, 11(3). <https://doi.org/10.3390/su11030896>
- [6] Kumar, P., Hama, S., Abbass, R. A., Nogueira, T., Brand, V. S., Wu, H. W., Abulude, F. O., Adelodun, A. A., de Fatima Andrade, M., Asfaw, A., Aziz, K. H., Cao, S. J., El-Gendy, A., Indu, G., Kehbila, A. G., Mustafa, F., Muula, A. S., Nahian, S., Nardocci, A. C., ... Shiva Nagendra, S. M. (2022). CO<sub>2</sub> exposure, ventilation, thermal comfort and health risks in low-income home kitchens of twelve global cities. *Journal of Building Engineering*, 61, 105254. <https://doi.org/10.1016/j.jobee.2022.105254>
- [7] Shin, H., Kang, M., Mun, S. H., Kwak, Y., & Huh, J. H. (2021). A study on changes in occupants' thermal sensation owing to CO<sub>2</sub> concentration using PMV and TSV. *Building and Environment*, 187, 107413. <https://doi.org/10.1016/j.buildenv.2020.107413>
- [8] Zhao, Q., Lian, Z., & Lai, D. (2021). Thermal comfort models and their developments: A review. *Energy and Built Environment*, 2(1), 21-33. <https://doi.org/10.1016/j.enbenv.2020.05.007>
- [9] Amoabeng, K. O., Opoku, R., Boahen, S., & Obeng, G. Y. (2022). Analysis of indoor set-point temperature of split-type

- ACs on thermal comfort and energy savings for office buildings in hot-humid climates. *Energy and Built Environment*, 4(3), 368-376.  
<https://doi.org/10.1016/j.enbenv.2022.02.006>
- [10] Castellano, J., Sanz, V., Cañas, E., & Sánchez, E. (2022). Effect of firing temperature on humidity self-regulation functionality in a ceramic tile composition. *Journal of the European Ceramic Society*, 42(13), 6236-6243.  
<https://doi.org/10.1016/j.jeurceramsoc.2022.05.058>
- [11] Chamberlain, A. T., Powell, C. D., Arcier, E., & Aldenhoven, N. (2022). The relationship between on-farm environmental conditions inside and outside cow sheds during the summer in England: can Temperature Humidity Index be predicted from outside conditions? *Animal - Open Space*, 1(1), 100019.  
<https://doi.org/10.1016/j.anopes.2022.100019>
- [12] Ravindra, K., Agarwal, N., & Mor, S. (2020). Assessment of thermal comfort parameters in various car models and mitigation strategies for extreme heat-health risks in the tropical climate. *Journal of Environmental Management*, 267, 110655. <https://doi.org/10.1016/j.jenvman.2020.110655>
- [13] Yan, H., Yang, L., Dong, M., Hu, B., Sun, Z., Shi, F., Yuan, G., & Bi, X. (2022). Thermal comfort in residential buildings using bimetal radiator heating vs. floor heating terminals. *Journal of Building Engineering*, 45, 103501.  
<https://doi.org/10.1016/j.jobe.2021.103501>
- [14] Trebilcock, M., Soto-Muñoz, J., & Piggot-Navarrete, J. (2020). Evaluation of thermal comfort standards in office buildings of Chile: Thermal sensation and preference assessment. *Building and Environment*, 183, 107158.  
<https://doi.org/10.1016/j.buildenv.2020.107158>
- [15] Rawal, R., Shukla, Y., Vardhan, V., Asrani, S., Schweiker, M., de Dear, R., Garg, V., Mathur, J., Prakash, S., Diddi, S., Ranjan, S. V., Siddiqui, A. N., & Somani, G. (2022). Adaptive thermal comfort model based on field studies in five climate zones across India. *Building and Environment*, 219, 109187.  
<https://doi.org/10.1016/j.buildenv.2022.109187>
- [16] Costa-Carrapiço, I., González, J. N., Raslan, R., & Sánchez-Guevara, C. (2022). Understanding the challenges of determining thermal comfort in vernacular dwellings: A meta-analysis. *Journal of Cultural Heritage*, 58, 57-73.  
<https://doi.org/10.1016/j.culher.2022.09.019>
- [17] Kim, J., Kim, S., Bae, S., Kim, M., Cho, Y., & Lee, K. I. (2022). Indoor environment monitoring system tested in a living lab. *Building and Environment*, 214, 108879.  
<https://doi.org/10.1016/j.buildenv.2022.108879>
- [18] Konstantinou, C., Constantinou, A., Kleovoulou, E. G., Kyriacou, A., Kakoulli, C., Milis, G., Michaelides, M., & Makris, K. C. (2022). Assessment of indoor and outdoor air quality in primary schools of Cyprus during the COVID-19 pandemic measures in May–July 2021. *Heliyon*, 8(5), e09354.  
<https://doi.org/10.1016/j.heliyon.2022.e09354>
- [19] Liu, S., Cao, Q., Zhao, X., Lu, Z., Deng, Z., Dong, J., Lin, X., Qing, K., Zhang, W., & Chen, Q. (2020). Improving indoor air quality and thermal comfort in residential kitchens with a new ventilation system. *Building and Environment*, 180, 107016.  
<https://doi.org/10.1016/j.buildenv.2020.107016>
- [20] Sahu, V., & Gurjar, B. R. (2020). Spatial and seasonal variation of air quality in different microenvironments of a technical university in India. *Building and Environment*, 185, 107310.  
<https://doi.org/10.1016/j.buildenv.2020.107310>
- [21] Wallis, S. L., Hernandez, G., Poyner, D., Holmes, W., Birchmore, R., & Berry, T. A. (2019). Particulate matter in residential buildings in New Zealand: Part II. The impact of building airtightness, mechanical ventilation using simulated occupancy. *Atmospheric Environment: X*, 2, 100026.  
<https://doi.org/10.1016/j.aeaoa.2019.100026>
- [22] Kaushik, A. K., & Dhau, J. S. (2022). Photoelectrochemical oxidation assisted air purifiers; perspective as potential tools to control indoor SARS-CoV-2 Exposure. *Applied Surface Science Advances*, 9, 100236.  
<https://doi.org/10.1016/j.apsadv.2022.100236>
- [23] Bhat, M. A., Eraslan, F. N., Awad, A., Malkoç, S., Üzmez, Ö. Ö., Döğeroğlu, T., & Gaga, E. O. (2022). Investigation of indoor and outdoor air quality in a university campus during COVID-19 lock down period. *Building and Environment*, 219, 109176. <https://doi.org/10.1016/j.buildenv.2022.109176>
- [24] Babaoglu, U. T., Milletli Sezgin, F., & Yag, F. (2020). Sick building symptoms among hospital workers associated with indoor air quality and personal factors. *Indoor and Built Environment*, 29(5), 645-655.  
<https://doi.org/10.1177/1420326X19855117>
- [25] Hermawan, Prianto, E., Setyowati, E., & Sunaryo. (2019). The thermal condition and comfort temperature of traditional residential houses located in mountainous tropical areas: An adaptive field study approach. *International Journal on Advanced Science, Engineering and Information Technology*, 9(6), 1833-1840. <https://doi.org/10.18517/ijaseit.9.6.3560>
- [26] Blázquez, T., Suárez, R., Ferrari, S., & Sendra, J. J. (2023). Improving winter thermal comfort in Mediterranean buildings upgrading the envelope: An adaptive assessment based on a real survey. *Energy and Buildings*, 278, 112615.  
<https://doi.org/10.1016/j.enbuild.2022.112615>
- [27] Yang, X., Lyu, H., Li, J., Fu, F., & Zhou, H. (2022). Comprehensive design for a vernacular wood house with energy-saving process. *Sustainable Energy Technologies and Assessments*, 53(PB), 102571.  
<https://doi.org/10.1016/j.seta.2022.102571>
- [28] Jiang, F., Tao, S., Tao, Q., Li, Z., Yuan, Y., & Zheng, J. (2022). The effect of louver blinds on the wind-driven cross ventilation of multi-storey buildings. *Journal of Building Engineering*, 54, 104614. <https://doi.org/10.1016/j.jobe.2022.104614>
- [29] Liu, Q., Son, Y. J., Li, L., Wood, N., Senerat, A. M., & Pantelic, J. (2022). Healthy home interventions: Distribution of PM2.5 emitted during cooking in residential settings. *Building and Environment*, 207(PB), 108448.  
<https://doi.org/10.1016/j.buildenv.2021.108448>
- [30] Nasrollahi, N., & Ghobadi, P. (2022). Field measurement and numerical investigation of natural cross-ventilation in high-rise buildings; Thermal comfort analysis. *Applied Thermal Engineering*, 211, 118500.  
<https://doi.org/10.1016/j.applthermaleng.2022.118500>
- [31] Nimarshana, P. H. V., Attalage, R. A., & Perera, K. K. C. K. (2022). Quantification of the impact of RANS turbulence models on airflow distribution in horizontal planes of a generic building under cross-ventilation for prediction of indoor thermal comfort. *Journal of Building Engineering*, 52. <https://doi.org/10.1016/j.jobe.2022.104409>
- [32] He, Y., Chu, Y., Zang, H., Zhao, J., & Song, Y. (2022). Experimental and CFD study of ventilation performance enhanced by roof window and mechanical ventilation system with different design strategies. *Building and Environment*, 224. <https://doi.org/10.1016/j.buildenv.2022.109566>
- [33] Rangel, C. G., Rivera-Solorio, C. I., Gijón-Rivera, M., & Mousavi, S. (2022). The effect on thermal comfort and heat transfer in naturally ventilated roofs with PCM in a semi-arid climate: An experimental research. *Energy and Buildings*, 274, 112453. <https://doi.org/10.1016/j.enbuild.2022.112453>
- [34] Maghrabie, H. M., Abdelkareem, M. A., Elsaid, K., Sayed, E. T., Radwan, A., Rezk, H., Wilberforce, T., Abo-Khalil, A. G., & Olabi, A. G. (2022). A review of solar chimney for natural ventilation of residential and non-residential buildings. *Sustainable Energy Technologies and Assessments*, 52(PB), 102082. <https://doi.org/10.1016/j.seta.2022.102082>

- [35] Singh Rajput, K., & Bartaria, V. N. (2022). Experimental study of vertical air temperature distribution and ventilation with energy saving using solar chimney. *Materials Today: Proceedings*, 63, 692-698.  
<https://doi.org/10.1016/j.matpr.2022.04.914>
- [36] González-Prieto, D., Fernández-Nava, Y., Megido, L., & Prieto, M. M. (2023). Economic and environmental prioritisation of potential retrofitting interventions in electricity decarbonisation scenarios: Application to a heritage building used as offices. *J. Build. Eng.*, 72, 106561.  
<https://doi.org/10.1016/j.jobe.2023.106561>
- [37] Hansen, R. N. et al. (2024). Environmental consequences of shifting to timber construction: The case of Denmark. *Sustain. Prod. Consum.*, 46, 54-67.  
<https://doi.org/10.1016/j.spc.2024.02.014>
- [38] Hernández, H., & Molina, C. (2023). Analyzing energy poverty and carbon emissions in a social housing complex due to changes in thermal standards. *Energy Sustain. Dev.*, 77, 101347.  
<https://doi.org/10.1016/j.esd.2023.101347>
- [39] Sutkowska, M., Stefańska, A., Vaverkova, M. D., Dixit, S., & Thakur, A. (2024). Recent advances in prefabrication techniques for biobased materials towards a low-carbon future: From modules to sustainability. *J. Build. Eng.*, 91, 109558.  
<https://doi.org/10.1016/j.jobe.2024.109558>

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