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Achieving low energy architecture from poor air quality in highland wooden houses at PM 2.5 content

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ABSTRACT

Waste of energy is a global problem that is included in the field of architecture. Material selection is one of the factors that need to be considered in order to create an energy-efficient residential house. Residential houses with wooden walls are sustainable and energy efficient. Residents of wooden houses in the highlands use to heat their rooms. The use of fireplace creates smoke, which causes poor indoor air quality. The purpose of this research is to reveal the air quality in wooden houses and the achievement of energy efficient houses. The study used a quantitative method by measuring the PM 2.5 variable which is the indoor air quality variable. The research object is 39 wooden houses in the highlands. Measurements were carried out in four rooms, namely outdoor, terrace, living room and kitchen. Data analysis was performed using graphical methods and statistical tests. The results showed that the PM 2.5 content in wooden houses was relatively high and could affect the health of the occupants. Adjustment of residential elements can be a solution in overcoming poor air quality in wooden-walled residential houses that use traditional fireplaces. This research presents a novel approach by combining energy efficiency analysis with direct measurements of indoor air pollutants (PM 2.5) in traditional wooden houses, a topic that remains underexplored in existing architectural and environmental health research.

Keywords: fireplace, local wisdom, low-income communities, air quality, housing sustainability.

INTRODUCTION

Waste of energy in buildings occurs in almost all countries. The building cover is one of the dominant factors influencing energy wastage. Approximately 98% of energy wastage occurs due to the use of inappropriate building covers (Nutkiewicz et al., 2022). Architects need to play more roles in order to reduce energy waste. The design style in architecture is mostly towards energy efficient buildings. Architectural design, saving energy will create sustainability for human life. One architectural design that supports sustainability is a biophilic design (Zhong et al., 2022).

Sustainable design is also seen in vernacular houses. It is an alternative in realizing low-energy architecture. The determining factor in the realization of low energy architecture is the comfort of building occupants. They do not require additional tools to create thermal comfort because the building has made them comfortable. Convenience related to energy saving is in terms of thermal and health comforts. Thermal discomfort will make the occupants use air conditioning equipment, while discomfort in health will make them expend extra resources in overcoming health problems. Both aspects of discomfort will create a waste of energy. Research shows that improving the energy performance of social housing, both to reduce energy demand and to enhance indoor microclimatic conditions and residents' quality of life (Ascione et al., 2024).

At present, countries in the world are always trying to realize zero energy buildings by issuing regulations on the use of energy in buildings. The application of passive building strategies is necessary to create zero energy buildings (Borrallo-Jiménez, 2022). The application of rules to achieve zero energy buildings is often limited to high-rise buildings. Meanwhile, plain buildings such as plain houses cannot be managed properly. The realization of a zero energy building cannot be separated from the health factor of building occupants.

Health in a certain area is of particular concern to the government with the frequent emergence of viruses and increasing amounts of pollution. Cities as part of the country need to pay attention to health criteria (Kyprianou et al., 2022). The Covid-19 pandemic period has caused changes in people's behavior, especially those who work from home. All activities carried out in the house increase the waste of energy in terms of using air conditioner (AC). Energy waste is closely related to health factors (Toosty et al., 2022). Research by Maiques et al. shows that building orientation plays a role in the use of both natural and mechanical ventilation. HVAC energy consumption is reduced by 42% with a south-facing orientation when using natural ventilation in Mediterranean regions.

Improved energy performance of buildings can be evaluated together with good thermal comfort and Indoor air quality (IAQ). Indoor environmental quality (IEQ), actual energy calculation and performance, investment and life cycle costs (LCC) are the defining variables in the evaluation of energy use. Ventilation air flow rates, temperature, and CO were measured concurrently with the occupant questionnaire survey which was conducted in parallel with the on-site measurements. Questionnaire measurement to obtain subjective results from the perception of thermal comfort of building occupants (Ahmed et al., 2022). Ventilation plays a crucial role in reducing indoor pollutants and ensuring acceptable levels of IAQ (Alameddine et al., 2022). A study related to air quality was also conducted by Yu Zhao et al. in the case of restaurants, showing that changes in air quality occur due to the influence of the number of people in the room (Zhang et al., 2022).

Convenience in health is widely discussed in current research, especially because of the Covid-19 virus that has hit the world. One of the health factors in the building is the availability of clean air inside the room. The air in the room contains many substances, both positive and negative substances. One of the negative substances contained in the air is particulate matter (PM). Initially, WHO included PM 2.5 as a health requirement indoors with a value of 10 μg/m^3. In September 2021, WHO started changing the maximum requirement for PM 2.5 to 5 μg/m^3. This reduction in maximum requirements as a standard must be met so that indoor air quality becomes healthier (Zhao et al., 2022).

A PM 2.5 monitoring is carried out to get clean air. It needs to be done in all types of buildings so that sick building syndrome does not occur. The monitoring can be done publicly such as schools or residential buildings. Monitoring at school will make children able to learn more comfortably (Alameddine et al., 2022). The PM monitoring is also carried out in underground buildings. The air content underground is considered to be of low quality. PM monitoring research in underground buildings are used for passengers. This aims to reveal how low the quality of the underground air used for transportation stops (Zhang et al., 2022).

Pollutant exposure is affected by building ventilation. The ventilation also affects the PM content in the building. The PM content outside and inside buildings connects closely. The type of ventilation will affect the relationship between the two (Abdel-Salam, 2022). Ventilation in the building determines the building in energy saving (Abdullah, 2022). PM exposure in living rooms and bedrooms can be greater than in other spaces. PM exposure is influenced by architectural elements such as volume of space, proximity of buildings to roads (Abdel-Salam, 2022).

Building materials also affect the PM content in the building. Building materials can make dust particles fly in the air. The use of wood as a wall material in vernacular architecture also affects the PM content in the air. Vernacular architecture is unique in obtaining air in space. It is made from soil excavation that also has more value in terms of sustainability (Taher Tolou Del et al., 2022). Vernacular architecture has gained much attention in recent years for its energy saving and environmental adaptability characteristics. It is considered as a potential method for reducing energy consumption and important cultural heritage. However, under rural modernization and urbanization, vernacular architecture is threatened with extinction (Wang et al., 2022).

A wooden house is a valuable vernacular architecture and needs to be preserved. One of the causes of the destruction of wooden houses is due to fire. The government needs to maintain wooden houses by making regulations so that people are careful in maintaining vernacular architecture (Kristoffersen and Log, 2022). Local wisdom possessed by vernacular architecture needs to be maintained by creating comfort and health for residents of vernacular houses. Research was conducted to improve the comfort and health quality of vernacular homes. Research can be done by predicting air content and looking for solutions for space health solutions.

Research is carried out to produce a model so that it can predict future events. Prediction models can be used in a variety of ways. The use of algorithms is often done to get predictive models (Zhou and Ooka, 2022). Prediction of PM 2.5 indoors is an important matter as a basis for room design. Field studies can be carried out in research of PM 2.5 content indoors. Analysis of the characteristics of PM 2.5 is one of the results that can be obtained to analyze indoor air quality (Zhou et al., 2022). Regression analysis can also make prediction models in indoor air quality research. Predictions found can be the basis for establishing a healthy home.

This study aims to reveal the air quality in wooden house and seek architectural solutions so that residents are comfortable and healthy.

MATERIALS AND METHODS

Determining time of indoor air quality data measurements uses time in the long or short term. Long-term measurements take 8 hours, while short-term measurements can take 1 hour. Taking long-term or short-term time is adjusted to the length of human activity (Ntanos et al., 2022). Research time taking is based on human activity in the room.

Pollutant analysis in residential homes can be measured in oudoor and indoor buildings. The correlation of the content of particles in the air between the outdoor and indoor spaces can be an analytical tool in air quality research (Alonso et al., 2022). Correlation between variables can be an analytical tool to predict indoor air quality. The use of the Pearson correlation in statistics can be used to analyze research results (Zhang et al., 2022). The method used is a combination of qualitative and quantitative methods that can create more comprehensive research results.

The research location is in Indonesia, situated in the central part of Java Island, (Figures 1–3).

The main characteristics of the houses sampled are wooden-walled houses. Simple residential houses in the highlands, mostly inhabited by economically weak groups. PM 2.5 data was taken from four rooms, namely the outdoor room, terrace, living room and kitchen. The data was taken during activity time at the residence, starting at 06.00–21.00. Data collection is done every 15 minutes. Data analysis was carried out using graphs by comparing thirty-six research objects. Minimum, maximum, and average data are displayed and analyzed descriptively. Regression analysis was used to create a predictive model for PM content in wooden houses.

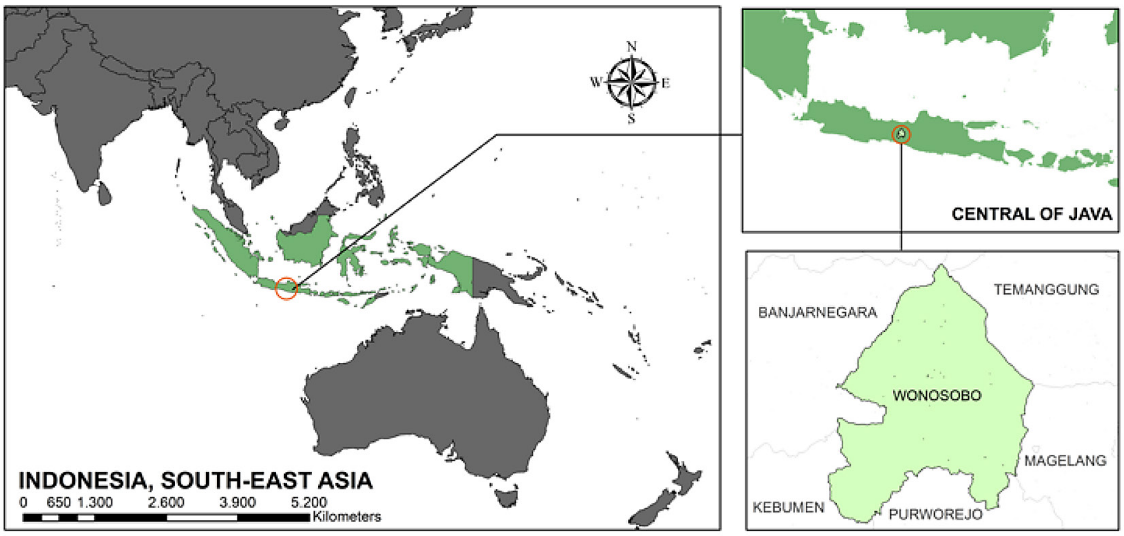

Figure 1. Research object location

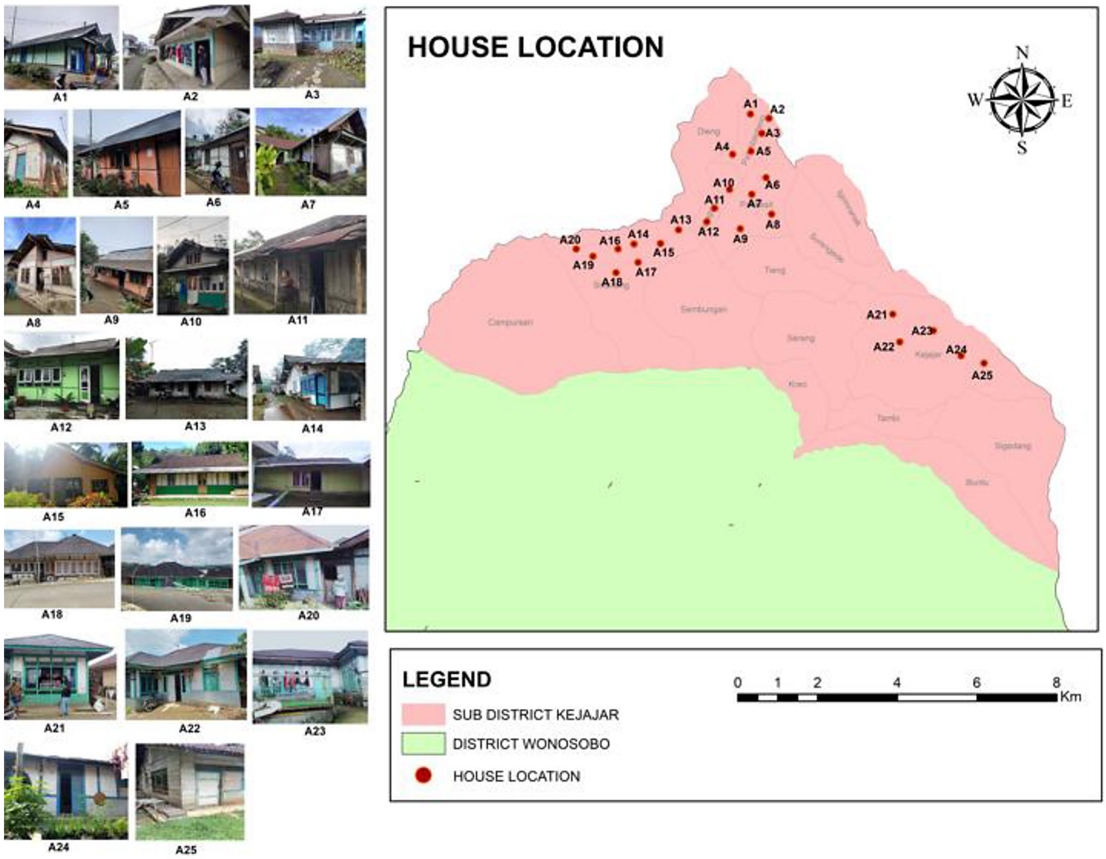

Figure 2. Research object location in Sub District Kejajar

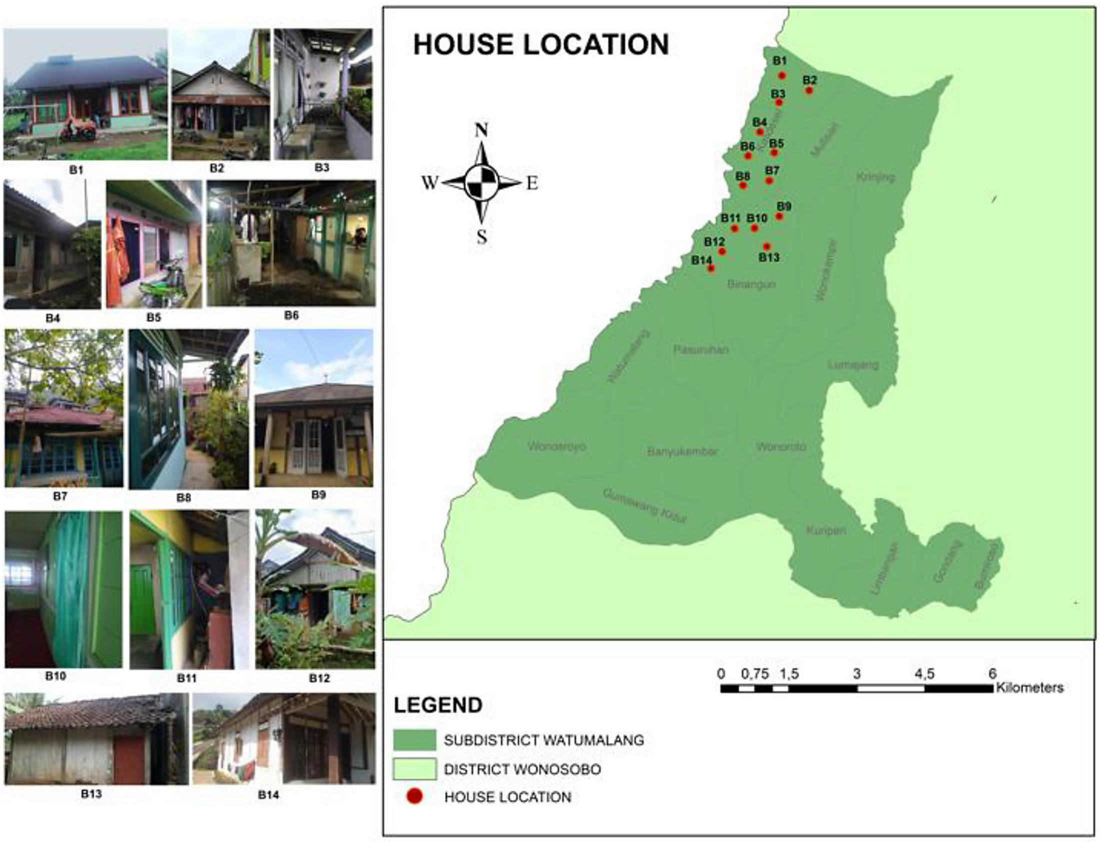

Figure 3. Research object location in sub-district Watumalang

RESULTS AND DISCUSSION

Most of the results of PM2.5 measurements outdoors range from 0–100 µg/m^3 (Figure 4). Outdoors in some houses looks more than 100 µg/m^3 to 250 µg/m^3. Outdoor houses 9, 15 and 28 have high PM 2.5 values. The tendency of houses to have a high PM 2.5 when the house is exposed to smoke, both smoke from burning garbage outside the house and smoke from burning traditional stoves inside the house. The smoke caused by traditional stoves spreads outside the house and affects the PM2.5 content outdoors.

The PM 2.5 content in the terrace is different from that in the outdoor. Terrace does not display PM 2.5 content which is too volatile. There is only one residential terrace whose PM 2.5 content is almost 1000 µg/m^3 (Figure 5). House 15 is the only residential house that has a terrace with a PM 2.5 content close to 1000 µg/m^3. The terraces of houses 8, 9, 14 and 20 have a higher content than other houses. The four terraces of residential houses show contents close to 200 µg/m^3 at any given hour (Figure 5).

The living room of the research object has a fluctuating PM 2.5 content (Figure 6). PM2.5 content in the living room is not evenly distributed. The PM2.5 content in some residential houses is close to 1000 µg/m^3. Most of the other residential houses have variations in PM 2.5 content close to 400 µg/m^3. Residential houses 1, 8, 10, 14, 20, 27 reach their highest point at around 10 am, 1 pm to 7 pm when residents carry out cooking activities using traditional stoves. The resulting smoke moves towards the living room. At certain times, occupants also carry out smoking activities in the living room so that the living room has a high concentration of PM 2.5 as well

The kitchen as the center of cooking activity will have the highest PM 2.5 content during cooking. The traditional stove used for cooking has a PM 2.5 content of up to 1000 µg/m^3. Very high PM 2.5 content occurs in the kitchen because the kitchen uses a traditional fire stove. Nearly half of the houses that were used as research objects carried out cooking activities when the measurement of PM 2.5 content was carried out for one full day. The measurements taken do not limit the occupant's activities so that the occupants are active as usual. Fluctuations in PM 2.5 content in the kitchen were seen ranging from 200–1000 µg/m^3 (Figure 7). Conditions in the kitchen are fluctuating and tend to have high PM 2.5 content, making it important to ventilate in the room so that air exchange runs smoothly.

The amount of data is 2379 data with the smallest PM 2.5 content of 10 µg/m^3 occurring in outdoor and living rooms. The highest PM 2.5 content occurred in the living room and kitchen at 999 µg/m^3 (Table 1). The smallest PM 2.5 content occurs when there is no combustion activity that causes smoke. When the occupants of the house have activities that cause smoke, the PM2.5 content in a room will experience a sharp increase. This sharp increase occurred more in the living room and kitchen. Judging

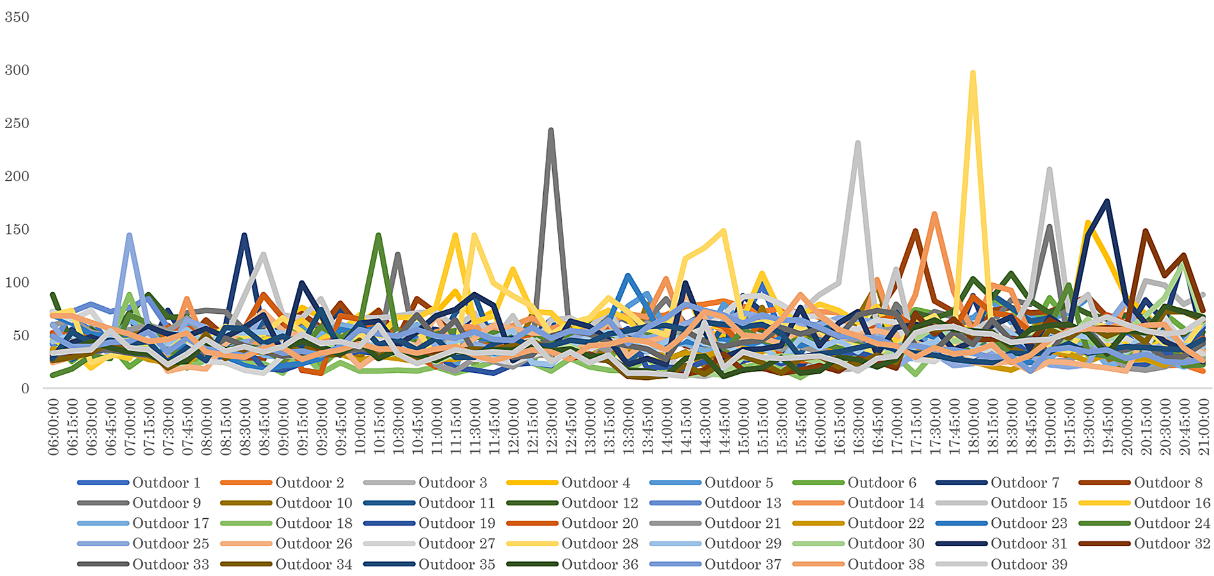

Figure 4. PM 2.5 concentration at outdoor

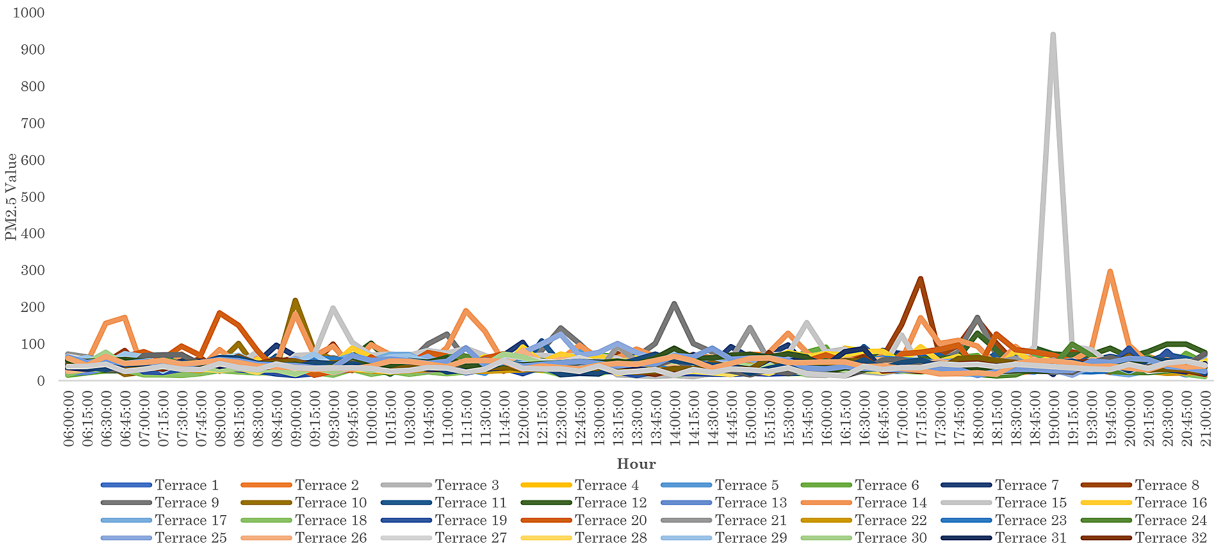

Figure 5. PM2.5 concentration at terrace

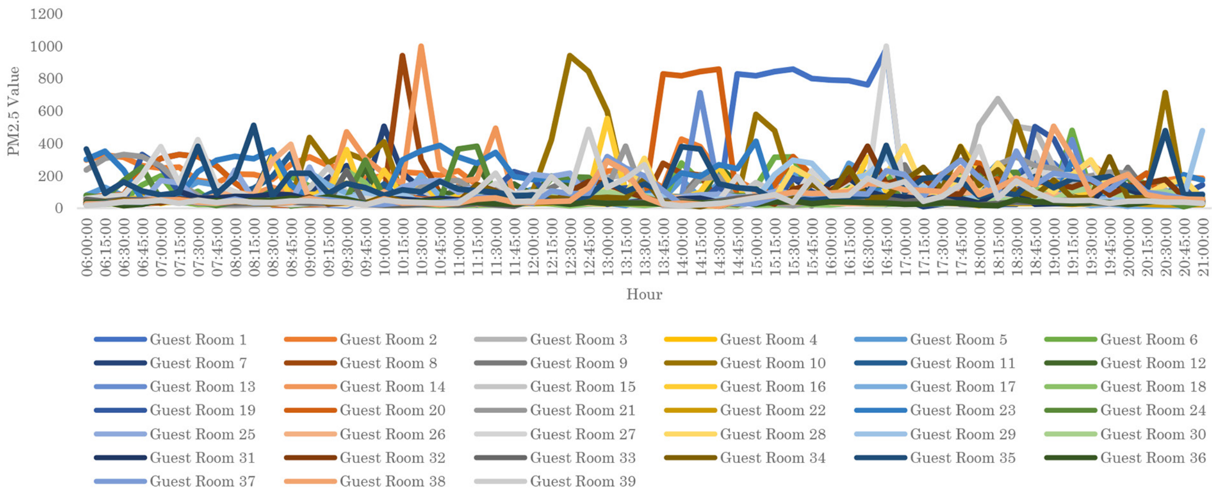

Figure 6. PM 2.5 concentration in living room

from the average PM 2.5 content, the largest occurs in the living room. The second largest average occurs in the kitchen. The activities of the occupants in the living room who often smoke cause there is often smoke there. In addition, the smoke from the traditional stove in the kitchen also flows into the living room which is also used as a family room. Residents of the house is one of the factors that affect environmental conditions. The perception of the occupants of the house is very important to know in order to create a healthy and energy efficient environment (Ntanos et al., 2022).

The relationship between PM 2.5 content in the four spaces (outdoor, terrace, living room and kitchen) was analyzed using the Analysis of Variant (ANOVA) using the Bonferroni method (Table 2). The results of the different tests showed that there was no significant difference in the PM 2.5 content in outdoor and terrace. The average PM 2.5 content in the two chambers was around 45 $\mu g/m^3$. The relationship between PM 2.5 content between the terrace, living room and kitchen also has a significant difference. Differences in PM 2.5 content in several spaces show differences in occupant activity in each room. In addition, the condition of indoor ventilation in each different room will cause differences in clean air exchange.

The influence between variables needs to be comprehended so that predictions and solutions can be made to create healthy buildings. Research on the effect of PM 2.5 content between outdoor and indoor spaces has been carried out by many researchers and found that there is an influence

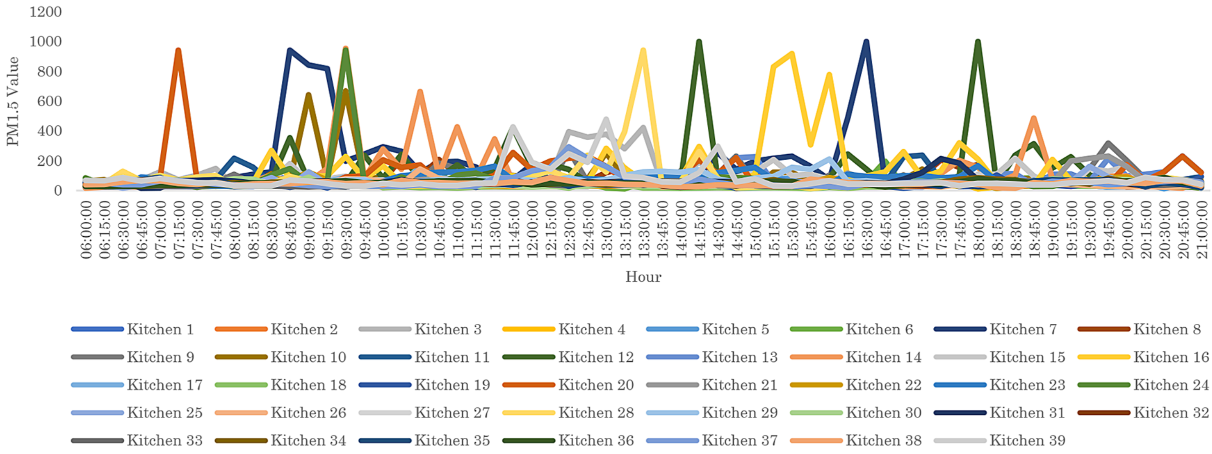

Figure 7. PM2.5 concentration in kitchen

Table 1. Descriptive data

Room	N	Mean	Std. Dev	Std. Error	Min	Max
Outdoor	2.379	45.91	20.473	0.420	10	297
Terrace	2.379	45.24	27.902	0.572	11	941
Living room	2.379	92.95	108.472	2.224	10	999
Kitchen	2.379	67.65	81.818	1.677	12	999
Total	9.516	62.94	72.764	0.746	10	999

Table 2. ANOVA

(I) Room	(J) Room	Mean difference (I-J)	Std. Error	Sig.
Outdoor	Terrace	0.665	2.033	1.000
	Living room	-47.044*	2.033	0.000
	Kitchen	-21.744*	2.033	0.000
Terrace	Outdoor	-0.665	2.033	1.000
	Living room	-47.709*	2.033	0.000
	Kitchen	-22.409*	2.033	0.000
Living room	Outdoor	47.044*	2.033	0.000
	Terrace	47.709*	2.033	0.000
	Kitchen	25.300*	2.033	0.000
Kitchen	Outdoor	21.744*	2.033	0.000
	Terrace	22.409*	2.033	0.000
	Living room	-25.300*	2.033	0.000

between PM 2.5 content in outdoor and indoor spaces. The outdoor air conditioning, which has a lot of pollution, causes the indoor air conditioning to become unhealthy. In rural residences, the outside air conditioning is quite clean and there is no pollution from factories or industrial areas. Consequently, the effect of PM 2.5 content between outdoor and indoor is not too significant. Residents of rural houses do more activities that produce smoke from inside the house, such as cooking or smoking. The influence of PM 2.5 content between interior spaces is important to analyze so that it can be identified which room most influences the PM 2.5 content of other spaces. The results of the regression test showed that there was an effect of PM 2.5 content between rooms, both outside and inside (Table 3).

Several models of the effect of PM2.5 content between rooms in a wooden house can be seen in Equations 1 to 6.

$$PM2.5_{terrace} = 26{,}658 + 0.405\ PM2.5_{outdoor} \quad (1)$$

$$PM2.5_{living\ room} = 76{,}643 + 0.355\ PM2.5_{outdoor} \quad (2)$$

$$PM2.5_{kitchen} = 43{,}972 + 0.516\ PM2.5_{outdoor} \quad (3)$$

$$PM2.5_{outdoor} = 36{,}047 + 0.218\ PM2.5_{terrace} \quad (4)$$

$$PM2.5_{outdoor} = 44{,}730 + 0.013\ PM2.5_{living\ room} \quad (5)$$

$$PM2.5_{outdoor} = 43{,}722 + 0.032\ PM2.5_{kitchen} \quad (6)$$

The influence model can predict the PM 2.5 content in a room both indoors and outdoors. Regression analysis is still mostly done to make an analysis of the influence between variables. Regression analysis can be done using several analytical tools (Chaibi et al., 2022).

The prediction model for PM 2.5 content in all rooms still exceeds the threshold required for health. The content of PM 2.5 in wooden houses in the highlands causes poor air quality in wooden houses. Improvement of architectural elements in residential homes is needed in order to improve poor air quality. Improvements can be made with air cleaning equipment or by adding ventilation so that air exchange can be smoother.

The addition of air cleaning equipment will create an extra energy burden in the building, causing a waste of energy in the building. Energy use in buildings can be saved by enhancing energy saving elements such as photovoltaic (PV). Photovoltaic will store solar energy and convert it into electricity so that it can be used as a source of energy in the buildings (Nijmeh et al., 2022).

The performance of additional equipment such as Photovoltaic is affected by the cleanliness of the air in the surrounding environment. The dust content in the air will reduce the performance of the photovoltaic (Ahmad et al., 2022). The content of PM 2.5 in the air can reduce equipment performance. The interrelationship between additional equipment and PM 2.5 content makes it important to maintain equipment and purify air content in the environment. PV performance is also affected by air temperature and solar radiation so that PV placement in buildings needs to be put in the right place (Al-Ghezi et al., 2022).

Improvement of residential elements to realize clean air quality can be done in several ways, including:

1. Cross ventilation

Smooth airflow can be achieved with the cross-ventilation method. The use of cross ventilation cannot be applied to high-rise buildings in hot areas (Nasrollahi and Ghobadi, 2022). In low-rise buildings, cross ventilation is still relevant to use to facilitate the movement of air circulation. Cross ventilation will produce different wind rates at different types of ventilation. Windows with different lattice angles will cause different airflow (Tai et al., 2022). Wooden houses in the highlands tend to close the ventilation due to the low air temperature so that they do not produce cross ventilation. Air currents in wooden houses tend not to be felt. Residential houses need to make cross-ventilation in accordance with indoor conditions so that smoke can quickly escape and clean air is formed.

2. Roof opening

Research on the efficiency of roof openings against mechanical windows placed on walls shows results that the efficiency of roof windows is 1.62 better than mechanical windows in circulating air in the room (Wang et al., 2019). Some wooden houses in the highlands have implemented roof openings to drain smoke from the kitchen. The effectiveness of openings in the roof that exceed mechanical windows can be one of the solutions in improving poor indoor air quality due to smoke from the use of traditional stoves.

Table 3. Regression test

Variable	Constant	Coefficient	Sig
Outdoor to terrace	26.658	0.405	0.000
Outdoor to living room	76.643	0.355	0.001
Otudoor to kitchen	43.972	0.516	0.000
Terrace to outdoor	36.047	0.218	0.000
Living room to outdoor	44.730	0.013	0.001
Kithen to outdoor	43.722	0.032	0.000

Note: The Writer (2022).

3. Type or type of ventilation

Natural ventilation is considered better than mechanical ventilation in circulating air indoors (Kumar et al., 2022). Wooden houses in the highlands use natural ventilation. Yet, ventilation is not opened frequently because it avoids cold air temperatures. Natural ventilation still needs to be maintained, and it needs to be opened more often so that the smoke in the room can leave the room and be replaced with fresh air. The solution to cold air can be done by using an air temperature sensor that is applied to the ventilation.

4. Ventilation size

The rate of air movement will be free with the wide ventilation. The efficiency of openings in an area needs to be taken into account so that the ventilation openings are not too wide but are able to produce air movement rates that produce clean air (Xu et al., 2022). Wooden houses in the highlands have ventilation that is wide enough, but it is often closed. The size of the window is not a problem for the ease of air flow, but the intensity of opening the window is less. The occupants closed the windows because the cold air temperature from outside entered the room.

5. Chimney

The presence of a chimney can dispose smoke from indoors to outdoors. The chimney can also act as a heat sink from the sun (Maghrabie et al., 2022). The different shape of the chimney will make the direction of air circulation also different. The shape of the chimney needs to be adapted to the indoor conditions and equipment that causes smoke. Residential houses in Wonosobo do not use chimneys. Smoke in the room cannot escape smoothly. The use of chimneys for low-income people needs to be optimized by using cheap materials. The shape of the chimney also needs to be adapted to the conditions of the interior space and the fireplace used by the occupants of the wooden house.

6. Smoke absorber

The smoke absorber on the stove is an alternative that is often used to reduce the smoke content in the kitchen. The results of the study show that a combination of smoke absorbers and natural ventilation can reduce the content of particulate matter in the kitchen (Liu et al., 2022). Wooden houses in the highlands do not use smoke absorbers indoors. Residents consider that the use of smoke absorbing equipment requires a large amount of money. The occupants of the wooden houses in the highlands belong to the low-income community so that the procurement of equipment which is considered to require a large amount of money cannot be fulfilled. Making a smoke absorber indoors can be done using inexpensive materials so the costs required are not too high.

7. Location of doors and windows in the wind direction of the environment.

The kitchen as a place to put traditional stoves needs to be designed so that it has sufficient air circulation. Doors and windows are factors that affect airflow. The condition of doors that are often closed will cause obstruction to the flow of air in the room (Matongo et al., 2022). The kitchen of a wooden house in the highlands has a side or back door. The kitchen can be accessed from the side or back doors and these doors make airflow smoother.

8. Placement of traditional stoves close to the ventilation.

The location of the furnace affects the movement of smoke through the room. A furnace that is near ventilation will make the resulting smoke exposed to the wind flow from the existing ventilation. A smooth flow of wind will allow smoke to exit the room quickly. The spread of smoke can go to other rooms through the door that connects the kitchen to other rooms. The spread of smoke can be reduced to other rooms by closing the connecting door and placing a window close to the smoke source (Zheng et al., 2022).

9. Create ventilation near the traditional stove in the lower wall.

The location of the ventilation can make the smoke stream more effective. Traditional stoves are not too tall, so ventilation needs to be made above the floor that can be used to let smoke out of the wooden house.

CONCLUSIONS

Wooden houses as sustainable residences have weaknesses, namely the air quality in the room due to the use of traditional fire stoves. Lower to middle class people in the highlands use traditional fire stoves as heating equipment. The use of traditional stoves from generation to generation has become a warming culture that cannot be separated from the daily activities of the residents of the house. The use of this traditional stove creates smoke which causes high levels of

PM 2.5 in the room. The air quality inside the house is getting worse and can cause health problems for the occupants.

The architectural elements of wooden houses in the highlands are often not given proper attention and cannot create smooth air circulation. Improvement of residential architectural elements needs to be done to create good air quality. Several architectural elements can be added or adapted to the conditions of the substances contained in the air. Air circulation is an influential factor in creating healthy air quality. Adjustments to architectural elements are directed to create smooth air circulation. The cold air outside the house is one of the obstacles in getting air from outside into the house. Adjustments to residential elements need to be carefully considered so that air circulation can run smoothly while still creating thermal comfort in the room.

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