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Indoor Thermal Comfort in Tropical Urban Houses in Indonesia: The Effect of Outdoor Temperature and Windows

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Abstract: Indoor thermal comfort in tropical urban houses is important to manage because it determines the quality of life for the inhabitants. However, it is prone to sudden changes of temperature, especially in a developing country, such as Indonesia, where indoor air circulation is mainly supported by windows. This research aims to evaluate the indoor thermal comfort in Indonesian urban houses, and to analyse the correlation of outdoor temperature and the number of windows on the indoor temperature. This study took place in the Greater Bogor Area with a total of five houses. Outdoor and indoor temperatures were monitored in four areas for each home, which are the living room, bedroom, toilet, and terrace. The dry and wet temperatures were analysed to determine the indoor thermal comfort status based on ASHRAE (The American Society of Heating, Refrigerating, and Air Conditioning Engineers)-55. The correlation between outdoor temperature and the number of windows on indoor thermal comfort was analysed using multiple linear regression. Three of the five houses had areas that met the standard for thermal comfort. The areas were mainly the terrace and the bedroom. The average (standard deviation) of outdoor dry and wet temperatures was 27.79 ^{o}C (1.03 ^{o}C), and 25.59 ^{o}C (1.56 ^{o}C), respectively. While for the indoors, the average for dry and wet temperatures were 27.96 ^{o}C (1.87 ^{o}C), and 25.39 ^{o}C (2.31 ^{o}C). Outdoor temperature and number of windows showed insignificant correlation with indoor temperature (R^2: 0.1448; adj R^2: 0.08145; $p>0.121$), opposing the previous studies on the effect of outdoor temperature and number of windows on indoor temperature. Apart from this finding, the effect of windows/ventilation's presence on indoor thermal comfort cannot be undermined. As ventilation serves as a part of human adaptation to heat, it is becoming more important amidst the increased extreme heat caused by climate change.

Keywords: indoor; outdoor temperature; thermal comfort; tropical urban houses; windows

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1. Introduction

Climate change is resulting in rising global temperatures, which is exposing people to increasing heat [1]. This is dangerous to people, especially those who live in tropical climates, because the air is already warm and humid. A small rise in temperatures can trigger an increase in exposure to extreme heat, resulting in a dangerous condition for the population [2].

This rise in temperature is not solely affecting the outdoor environment, but also indoors. That is because of the effects of outdoor temperatures on indoor temperatures in a room with only natural air circulation, such as windows [3]. Unfortunately, most countries in the tropics are developing countries in which the houses depend on the regulation of their indoor air circulation through windows/ventilation. More people in urban tropical regions spend most of their time indoors; thus, the presence of windows in a room is essential.

Human has a limit for heat, which is 35 °C wet temperature. Exposure to wet temperatures above the limit can increase the risk of heat stress and heat stroke [4]. ASHRAE (The American Society of Heating, Refrigerating, and Air Conditioning Engineers) in standard 55 defines the thermal comfort standard, which includes parameters such as the clothing type and the activities being done. The standard has been widely used to assess indoor thermal comfort because it is more accurate in estimating the operational temperature experienced by the occupants [5]. Both the heat limit and the thermal comfort standard indicate the congenital factors in heat exposure.

The study that assesses the effect of windows/ventilation on indoor temperature is still limited. Kitagawa (2021) had analysed the effect of the type of windows on the indoor temperature in house rooms, suggesting horizontal pivot windows to achieve thermal comfort [6]. Meanwhile, Murtyas (2020) found an insignificant correlation between window area per interior volume and indoor air temperature [7]. None of these studies used the number of windows as the predictor for indoor temperature, which is what this study focuses on. The number of windows is considered to be more convenient to use by the majority of people because it is easier to measure, rather than the total opening area of windows or the type of windows. Therefore, this study has a crucial role in addressing the impact of windows on the natural air circulation to achieve indoor thermal comfort.

This research aims to assess the thermal comfort status of rooms in houses in the Greater Bogor Area, and to analyse the effect of outdoor temperature and the number of windows on indoor temperature. Temperatures are monitored outdoors and indoors in each house. This is to determine the thermal comfort status according to ASHRAE-55. The information on the number of windows in each room is collected through observation. The temperature and the number of windows data are quintessential to assess the effect of outdoor temperature and the number of windows on indoor temperature. The results of this study highlight the outdoor conditions and the effect of the room design on indoor thermal comfort.

2. Method

2.1. Study Location

This study is located in the Greater Bogor Area, which consists of Bogor City and Bogor Region, West Java, Indonesia. The Greater Bogor Area is a part of Greater Jakarta. Bogor City is about 60 km south of the Capital City of Jakarta. Bogor City is geographically located in 106°43'30"E – 106°51'00" E and 6°30'30"S – 6°41'00"S, covering an area of 118.5 km^2 with 190 – 350 m above the sea surface. It has a monthly average of air temperature of 33.9 °C, ranging from 18.8 °C to 36.1 °C. The precipitation reaches an average of 3,654 per year, with a monthly average range of 79 – 652 mm and an average of 14 days of rain per month. Other meteorological conditions are the average relative humidity of 70% and an average wind speed of 2 km/h, directing towards north east [8]. Built-up areas cover a total area of 4,433.40 hectares, or approximately 37.23% of the total area of Bogor City. These areas include commercial land, residential areas, planned housing, military complexes, palaces, industrial areas, terminals, and substations. The built-up areas in Bogor City are dominated by residential areas, covering 3,135.79 hectares (26.46%), which include healthcare, educational, religious, and office facilities [9].

Bogor Regency is adjacent to Bogor City in 6°18' to 6°47' South Latitude and between 106°01' to 107°10' East Longitude. The total area of Bogor Regency covers 2,999.78 km^2, consisting of 416 villages. In 2024, the highest precipitation is in November with 731 mm, and the lowest is in July with 62 mm. The average air temperature is 24.4 °C, with the highest and the lowest recorded in October (35.9 °C) and September (15.5 °C), respectively [10]. The population density in Bogor Regency is 1.881 [11].

2.2. Data Collection

The data collection activities were part of the Integrated Environmental Engineering Practicum 1 Course. Therefore, students were participating in acquiring the data. There were five teams in the class, with each team assigned to collect data in a house. Thus, the study was conducted in five houses across Bogor City and Bogor Region, West Java, Indonesia (**Figure 1**).

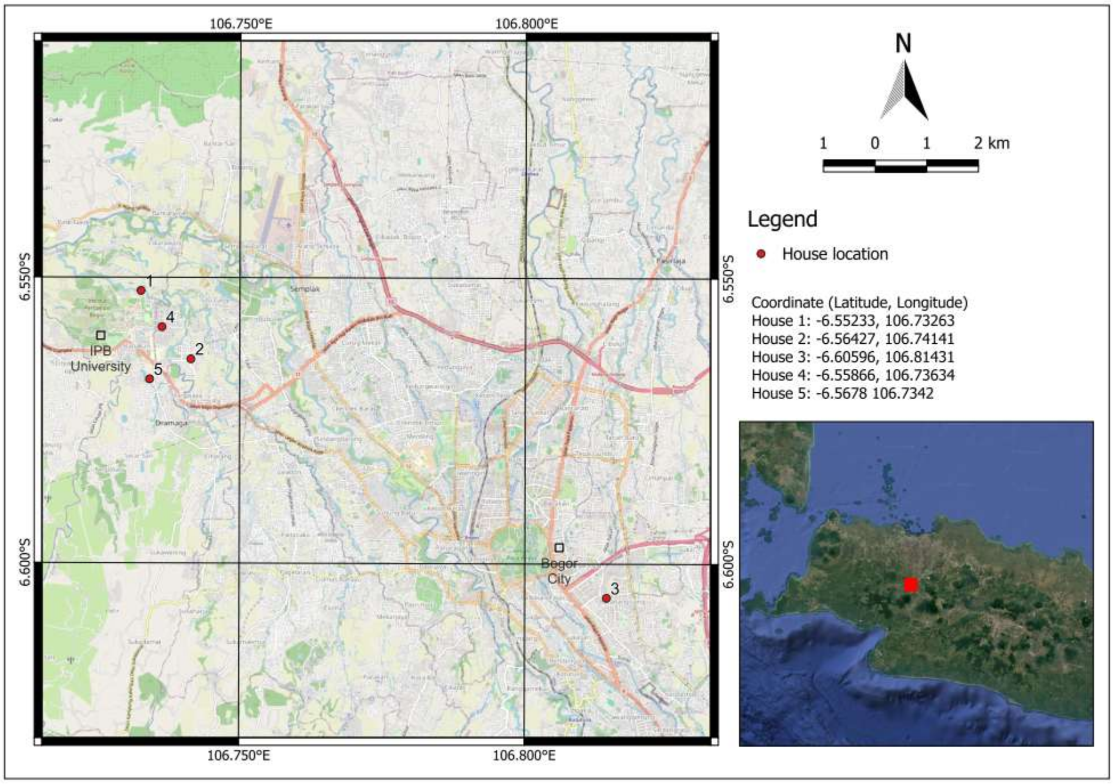

Figure 1. Study Location Map

The total point of observation in each house was four, with one point in the terrace (outdoor), and the other three points inside the home, including the bedroom, living room, and toilet. For each home, observation and temperature data collection were held on a day between 29 August and 12 September 2025. Dry and wet temperatures were measured using dry and wet bulb thermometers, respectively. The temperature was measured once in each room with two repetitions for each room. The temperature measurement location in each room is illustrated in **Figure 2**. The house coordinate was collected using phone GPS. The number of windows in each room was identified during the observation. The house floor plan showing the location of the room and its window(s), completed with wind direction legend, was collected to support the number of windows data.

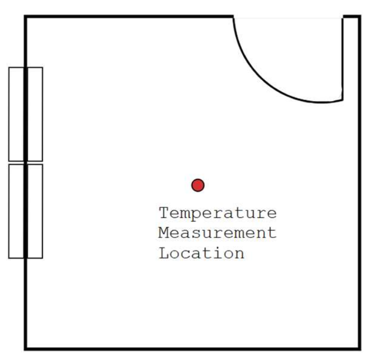

Figure 2. Temperature Measurement Location

2.3. Data Analysis

The location coordinate (latitude, longitude) was collected to determine the altitude using a free web-based elevation finder [12]. Using a psychrometric calculator, the dry and wet temperatures, along with the altitude, were used as inputs to calculate relative humidity (%), dew point temperature (°C), enthalpy (kJ/kg), specific volume (m^3/kg), and water vapor content (g/kg) [13]. Thermal comfort was estimated according to ASHRAE-55 2023 edition, with dry temperature and relative humidity as the data input. ASHRAE Standard 55 about Thermal Environmental Conditions for Human Occupancy with an objective to determine satisfactory thermal environment in occupied spaces by considering environemntal factors (temperature, thermal radiation, humidity, and air speed), and personal factors (activtiy and clothing) [5]. The method chosen for thermal comfort estimation is the PMV method. Mean radiant temperature was assumed to be equal to the dry temperature. Other assumptions were made for air speed, metabolic rate, and clothing level using the calculator default value of 0.1 m/s, 1 met (seated, quiet), and 0.61 clo (trousers, long-sleeve shirt), respectively [14]. The method to determine thermal comfort in SNI (Indonesia National Standard) 03-6572: 2001 is based on ASHRAE-55. Therefore, the thermal comfort status estimated using the web application is also aligned with SNI [15].

The thermal comfort status estimated by the psychrometric calculator was then described by considering the effect of the house type and its facing direction. Indoor-outdoor temperature relationship was analyzed using multiple linear regression (MLR), with the number of windows as the predictor variable. To test the model's fitness to MLR assumptions, the residuals were plotted as a residuals vs fitted value plot, histogram, and quantile-quantile (Q-Q) plot [16].

3. Results and Discussion

The total data point from the observation is 40, covering the dry and wet temperatures for four areas in each house, with a total of five houses across the Greater Bogor Area. All four houses are located in Bogor Regency, and only House 3 is located in Bogor City. Based on the house type, only House 4 is a co-living house, while the remaining houses are residential houses. The co-living house is characterised by rooms rented to the occupants, with each room getting its own toilet. There, each occupant can have access to the shared living room, kitchen, garage, and terrace. Meanwhile, the residential house is occupied by a family, with all areas only accessible to the family members.

3.1. Thermal comfort status

The overall dry temperature average was 27.91 °C (1.69 °C), and for wet temperature was 25.44 °C (2.13 °C). For the outdoor area, the average dry temperature was 27.79 °C (1.03 °C), and for wet temperature was 25.59 °C (1.56 °C). Meanwhile, the area indoors had an average dry temperature of 27.95 °C (1.87 °C), and an average wet temperature of 25.39 °C (2.31 °C). All rooms had a minimum of one window and a maximum of two windows. The type of windows varied from pivot/boven window, sliding window, and ventilation only. Data obtained from observations as shown in **Table 1**.

Table 1. Thermal Comfort Parameters

No.	House	Type	Room	Dry Temperature (oC)	Wet Temperature (oC)	Number of Windows	Elevation (m)
1	1	Residential	Bedroom	29	26	1	152.2
2	1	Residential	Bedroom	29	26	1	152.2
3	1	Residential	Living room	27	25	2	152.2
4	1	Residential	Living room	27	25	2	152.2
5	1	Residential	Toilet	28	25	1	152.2
6	1	Residential	Toilet	28	25	1	152.2
7	1	Residential	Terrace	28	26	NA	152.2
8	1	Residential	Terrace	28	26	NA	152.2
9	2	Residential	Living room	31	29.5	2	152.2

No.	House	Type	Room	Dry Temperature (oC)	Wet Temperature (oC)	Number of Windows	Elevation (m)
10	2	Residential	Living room	31	29.5	2	152.2
11	2	Residential	Bedroom	30.5	28	2	152.2
12	2	Residential	Bedroom	30.8	29.2	2	152.2
13	2	Residential	Toilet	30.2	29.6	1	152.2
14	2	Residential	Toilet	30	29	1	152.2
15	2	Residential	Terrace	28	28	NA	152.2
16	2	Residential	Terrace	27.9	27.9	NA	152.2
17	3	Residential	Bedroom	30	25	1	291.1
18	3	Residential	Bedroom	28	25	1	291.1
19	3	Residential	Living room	28	25	3	291.1
20	3	Residential	Living room	28	25	3	291.1
21	3	Residential	Toilet	28	26	1	291.1
22	3	Residential	Toilet	28	24	1	291.1
23	3	Residential	Terrace	26	24	NA	291.1
24	3	Residential	Terrace	26	24	NA	291.1
25	4	Co-living	Bedroom	27	24	1	187.4
26	4	Co-living	Bedroom	26	24	1	187.4
27	4	Co-living	Toilet	24	20	1	187.4
28	4	Co-living	Toilet	24	21	1	187.4
29	4	Co-living	Living room	28	24	2	187.4
30	4	Co-living	Living room	28	24	2	187.4
31	4	Co-living	Terrace	29	24	NA	187.4
32	4	Co-living	Terrace	29	24	NA	187.4
33	5	Residential	Bedroom	26	24	1	177.6
34	5	Residential	Bedroom	26	24	1	177.6
35	5	Residential	Toilet	26	24	1	177.6
36	5	Residential	Toilet	26	24	1	177.6
37	5	Residential	Living room	28	26	1	177.6
38	5	Residential	Living room	28	26	1	177.6
39	5	Residential	Terrace	28	26	NA	177.6
40	5	Residential	Terrace	28	26	NA	177.6
Average				27.91	25.44		
Std. Deviation				1.69	2.13		

None of the areas had wet temperatures of more than 35 °C, and only 25% of them complied with the thermal comfort standard (**Table 2**). They were in three out of five households, namely in the terrace for House 3, and in the bedroom and the toilet for both House 4 and House 5. The terrace in House 3, the bedroom in House 4, and the bedroom and the toilet in House 5 had dry and wet temperatures of 26 °C and 24 °C, respectively. The toilet in House 4 had a dry temperature of 24 °C, with wet temperatures of 20 °C and 21 °C. The dry and wet temperature data are shown in **Figure 3**.

Table 2. Thermal Comfort Parameters (Continuous)

No.	House	Type	Room	Relative Humidity (%)	Dew Point Temperature (oC)	Enthalpy (kJ/kg)	Specific Volume (m^3/kg)	Water Vapor Content (kg/kg)	Compliance with ASHRAE-55
1	1	Residential	Bedroom	79.1	25	81.4	0.9	143.3	N
2	1	Residential	Bedroom	79.1	25	81.4	0.9	143.3	N
3	1	Residential	Living room	85.2	24.3	77.1	0.9	137.3	N
4	1	Residential	Living room	85.2	24.3	77.1	0.9	137.3	N
5	1	Residential	Toilet	78.7	24	77.1	0.9	134.3	N
6	1	Residential	Toilet	78.7	24	77.1	0.9	134.3	N
7	1	Residential	Terrace	85.5	25.3	81.5	0.9	146.3	N
8	1	Residential	Terrace	85.5	25.3	81.5	0.9	146.3	N
9	2	Residential	Living room	89.6	29.1	98.3	0.9	183.8	N
10	2	Residential	Living room	89.6	29.1	98.3	0.9	183.8	N
11	2	Residential	Bedroom	82.9	27.2	90.7	0.9	164.5	N
12	2	Residential	Bedroom	88.9	28.7	96.7	0.9	180.1	N
13	2	Residential	Toilet	95.7	29.4	98.9	0.9	187.7	N
14	2	Residential	Toilet	92.9	28.7	95.8	0.9	179.7	N
15	2	Residential	Terrace	100	28	90.9	0.9	172	N

No.	House	Type	Room	Relative Humidity (%)	Dew Point Temperature (oC)	Enthalpy (kJ/kg)	Specific Volume (m^3/kg)	Water Vapor Content (kg/kg)	Compliance with ASHRAE-55
16	2	Residential	Terrace	100	27.9	90.4	0.9	171	N
17	3	Residential	Bedroom	67.2	23.2	77.9	0.9	130.8	N
18	3	Residential	Bedroom	78.8	24	78	0.9	136.7	N
19	3	Residential	Living room	78.8	24	78	0.9	136.7	N
20	3	Residential	Living room	78.8	24	78	0.9	136.7	N
21	3	Residential	Toilet	85.6	25.3	82.4	0.9	148.9	N
22	3	Residential	Toilet	72.3	22.5	73.7	0.9	125.1	N
23	3	Residential	Terrace	85	23.3	73.8	0.9	131	Y
24	3	Residential	Terrace	85	23.3	73.8	0.9	131	Y
25	4	Co-living	Bedroom	78.3	22.9	73.2	0.9	126.3	N
26	4	Co-living	Bedroom	85	23.3	73.2	0.9	129.3	Y
27	4	Co-living	Toilet	69.8	18.2	58.1	0.9	93.5	Y
28	4	Co-living	Toilet	76.9	19.7	61.7	0.9	103.3	Y
29	4	Co-living	Living room	72.2	22.5	73.1	0.9	123.4	N
30	4	Co-living	Living room	72.2	22.5	73.1	0.9	123.4	N
31	4	Co-living	Terrace	66.5	22.1	73.1	0.9	120.4	N
32	4	Co-living	Terrace	66.5	22.1	73.1	0.9	120.4	N
33	5	Residential	Bedroom	85	23.3	73.1	0.9	129.1	Y
34	5	Residential	Bedroom	85	23.3	73.1	0.9	129.1	Y
35	5	Residential	Toilet	85	23.3	73.1	0.9	129.1	Y
36	5	Residential	Toilet	85	23.3	73.1	0.9	129.1	Y
37	5	Residential	Living room	85.5	25.3	81.6	0.9	146.8	N
38	5	Residential	Living room	85.5	25.3	81.6	0.9	146.8	N
39	5	Residential	Terrace	85.5	25.3	81.6	0.9	146.8	N
40	5	Residential	Terrace	85.5	25.3	81.6	0.9	146.8	N
Average				82.44	24.56	79.68	0.9	141.64	
Std. Deviation				8.05	2.48	9.30	0.00	21.68	

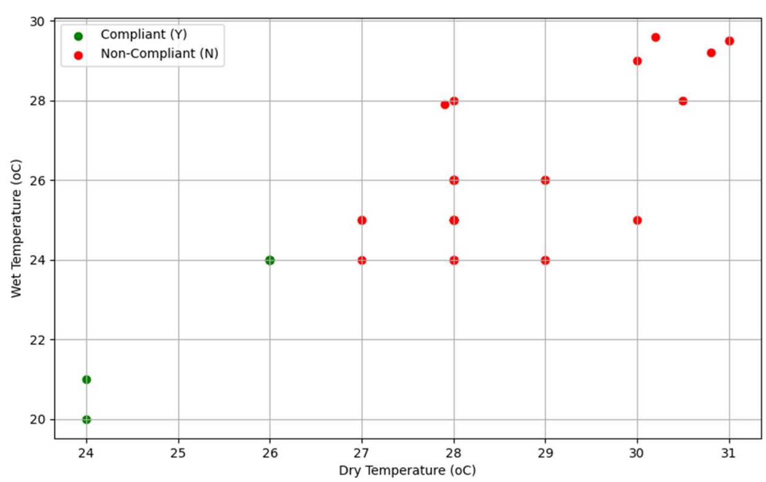

Figure 3. Temperature Distribution Based on Compliance with ASHRAE-55

House 3 was the only house where the outdoor condition met the thermal comfort standard, and also the only house located in Bogor City. Although House 4 and House 5 have different house types, both are located in Bogor Regency and have indoor areas that comply with the thermal comfort standard. House 4, as a co-living house, has a toilet placed in the bedroom, while House 5, as a common residential house, has the toilet separated from the bedroom. It indicates that thermal comfort outdoors did not straightforwardly affect the thermal comfort indoors.

3.2. Outdoor temperature and the number of windows correlation with indoor temperature

Outdoor dry temperature did not have a correlation with indoor dry temperature (R^2: 0.0886, p: 0.1102). Even after adding the number of windows as the second predictor, the correlation was still proven insignificant (R^2: 0.1448, adj R^2: 0.08145, p: 0.121). In consequence, the prediction model for indoor temperature based on outdoor temperature and number of windows showed poor R^2 with a value of 0.1448 (**Figure 4**). It means that the prediction model can only explain 14.48% of % variance of the sampling data, which is not acceptable.

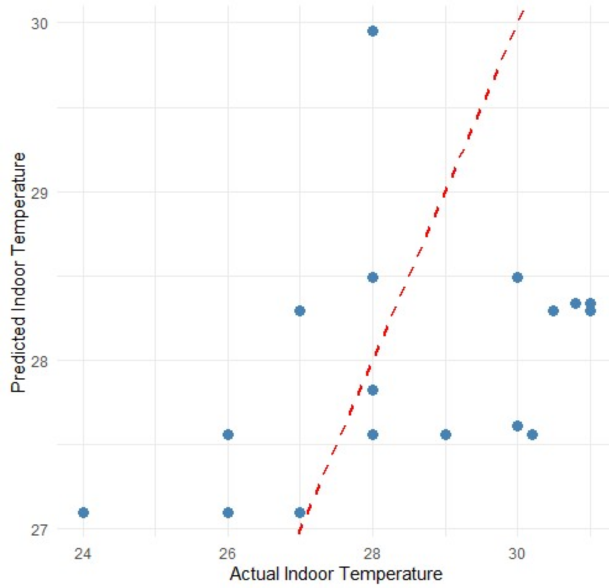

Figure 4. The Linear Regression Model for Indoor Temperature

The model's assumptions were checked by analysing the residuals through a histogram, Q-Q plot, and the residuals vs fitted values plot (**Figure 5**). The histogram indicates that the residuals have a distribution skewed to the left. From the Q-Q plot, the residuals are seen to be close to the reference line. Although the histogram shows a curve skewed to the left, the distribution can still be considered normal, thus meeting the first assumption for a regression model. However, the residuals vs fitted values plot indicates the heteroscedasticity of the residuals, shown by the fact that the residuals do not scatter randomly around 0. To solve for the heteroscedasticity, the data can be transformed into other forms, such as exponential or logarithmic, which this study does not cover.

The correlation test in this study is opposed to Zhang (2023), who found that outdoor and indoor temperatures are correlated [3]. But for the correlation between indoor temperatures and windows, this study further supports the finding from Murtyas (2020), in which no significant correlation is found between the two variables [7]. However, because the assumption check proved that the model violates homoscedasticity for residuals, no conclusion should be made as to whether this model supports or does not support findings from other studies.

This study poses limitations, mainly in the data collection. More houses need to be included for observations. The ideal number of samples can be predicted by using a formula to determine the sampling size from the population, such as Slovin's formula. If more data is acquired, a more accurate regression model can be developed.

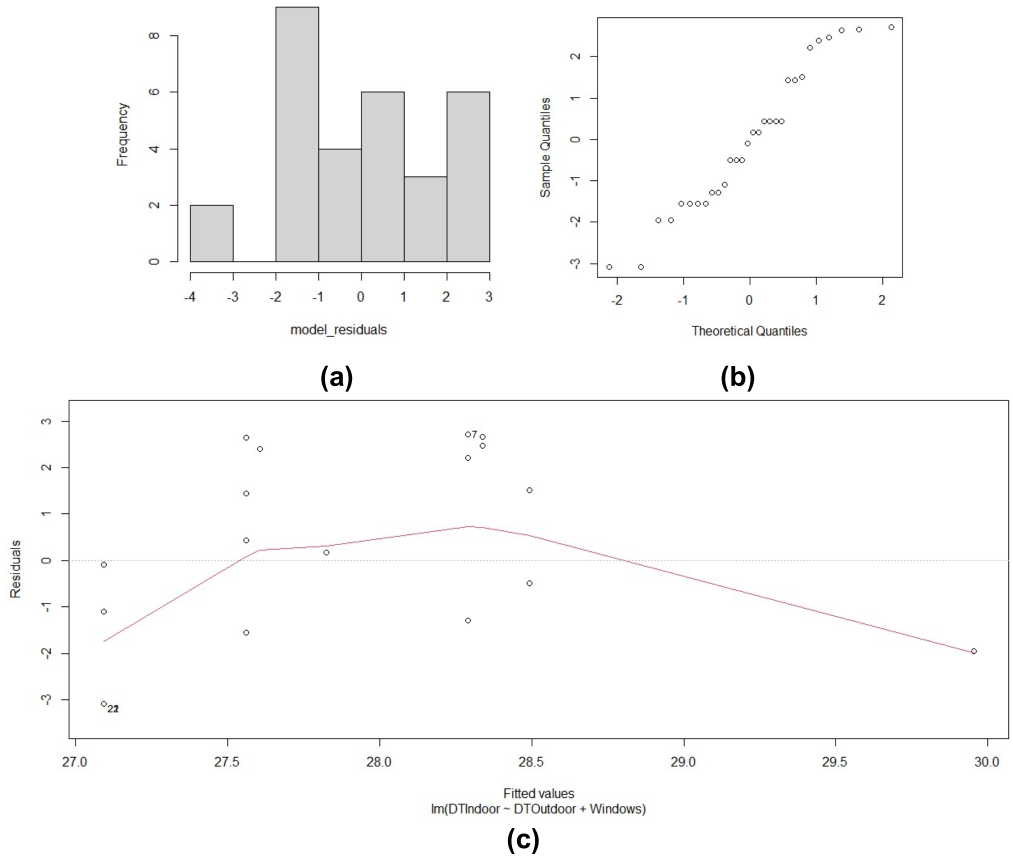

Figure 5. Regression Assumption Checking: (a) Histogram, (b) Normal Q-Q Plot, and (c) Fitted Values vs Residuals Plot

4. Conclusion

Of the total of five houses across the Greater Bogor Area, three of them had areas that complied with the thermal comfort standard. Those areas are the terrace in House 3, the bedroom and the toilet in House 4, and House 5. It had a dry temperature range of 24 – 26 °C, and a wet temperature range of 20 – 24 °C. The correlation of indoor temperature with outdoor temperature and number of windows was found to be insignificant (R2: 0.0886; p: 0.1102). Besides, the assumption check shows that the regression model for indoor temperature is violating the homoscedasticity for residuals. Therefore, the model is not accurate in predicting the indoor temperature condition in this study.

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