Dari Pesantren Menuju Ekopesantren: Penilaian Indeks Keberlanjutan dan Rekomendasi Peningkatan

From Pesantren Towards Ecopesantren: Sustainability Index Assessment and Improvement Recommendations

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Abstrak

Sebagai salah satu institusi pendidikan, pesantren memiliki potensi besar untuk mendukung pembangunan berkelanjutan, baik dalam lingkup lokal tempat pesantren beroperasi maupun pada skala yang lebih luas. Tujuan dari penelitian ini adalah untuk mengukur indeks keberlanjutan pesantren serta membangun tipologi pesantren berdasarkan karakteristik pemanfaatan ruang, guna menghasilkan rekomendasi perbaikan yang dapat meningkatkan indeks keberlanjutan. Penelitian ini merumuskan konsep indeks keberlanjutan berdasarkan tiga parameter utama: proporsi atap dengan albedo rendah (atap putih), proporsi pohon (ruang hijau), dan proporsi badan air (ruang biru) terhadap total luas lahan. Selain itu, dikumpulkan pula data terkait luas bangunan yang tidak menggunakan atap putih (ruang oranye) dan luas lahan terbuka (ruang abu-abu). Data dimensional dari lima parameter ini diperoleh menggunakan citra satelit Google Earth untuk 46 pesantren yang terdaftar dalam program Ekopesantren, yang tersebar di Pulau Sumatra dan Jawa. Analisis kluster hierarkis dengan metode Wald juga diterapkan untuk membangun tipologi pesantren dan merumuskan strategi peningkatan indeks keberlanjutan. Hasil analisis menunjukkan bahwa tidak ada pesantren yang memiliki indeks keberlanjutan lebih dari 50%, terutama karena kurangnya penggunaan atap putih dan ruang biru pada pemanfaatan ruang pesantren. Lima kluster yang terbentuk, yakni pesantren terbangun, pesantren menuju pembangunan, pesantren dengan persaingan ruang, pesantren hijau, dan pesantren padat, memberikan rekomendasi perbaikan yang spesifik untuk masing-masing tipe pesantren guna meningkatkan indeks keberlanjutan mereka.

Abstract

*As one of the educational institutions, **pesantren** have significant potential to contribute to sustainable development, both within the local context where they operate and in the broader environment. The aim of this study is to measure the sustainability index of pesantren and develop a typology based on space utilization characteristics to generate improvement recommendations that will enhance the sustainability index. The researcher formulated the sustainability index concept based on three parameters: the proportion of low-albedo roofs (white roofs), the proportion of trees (green space), and the proportion of water bodies (blue space) relative to the total land area. Additionally, data was collected on areas of buildings with non-white roofs (orange space) and open land areas (gray space). Dimensional data for the five parameters were obtained using Google Earth satellite images for 46 pesantren members of the Ecopesantren program, located across Sumatra and Java. Hierarchical cluster analysis was performed using the Wald method to categorize the pesantren and recommend strategies for enhancing their sustainability index. The analysis revealed that none of the pesantren had a sustainability index above 50%, primarily due to the limited use of white roofs and blue spaces. Five distinct clusters were identified: developed pesantren, pesantren toward development, pesantren with space competition, green pesantren, and compact pesantren. Specific recommendations for improving sustainability were proposed for each cluster type.*

***Keywords**: ecopesantren, green space, cluster analysis, Google Earth, sustainability index*

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Introduction

The impacts of climate change are becoming more pronounced by the day. The planet's annual average maximum temperature continues to rise every year, and with each passing year comes a new record holder for the hottest year in recorded history (Paddison, 2023). In Indonesia, the increase in temperature has also been felt so that the term "boiling heat" has emerged as a new concept that describes the intense heat during the day (Damiana, 2023). If no mitigation measures are taken, the increase in temperature will reach a point where there is no longer enough water to be used by the Earth's inhabitants who are increasing every day.

Indonesian people's awareness of climate change is still very weak (Putri et al., 2023). The level of global warming denialism in Indonesia and other Southeast Asian countries is high and is perpetuated by the mass media through news stories that 'downplay' the real risks and impacts of climate change occurring in their respective countries (Putri et al., 2023; Liu et al., 2020). Researchers have highlighted how rapid and grandiose development is prioritized to catch up with developed countries, while forgetting about nature conservation and the risks posed by nature being destroyed for the sake of development (Manzo et al, 2020; Liu et al, 2023).

In recent years, however, there have been major movements to mitigate climate change. The government, for example, has issued green building regulations, opened investment taps in the renewable energy sector, and conducted campaigns to save the remaining forests (Clemencon, 2023). Meanwhile, among religious circles, a number of discourses have also emerged that call themselves natural pesantren, natural boarding schools, or green pesantren as environmentally oriented religious education institutions (Amalia et al, 2023; Safei and Himayatuohmah, 2023; Quddus, 2020).

Islam strongly supports efforts to preserve and restore the environment (Abta, 2004; Khalid, 2018; Mangunjaya, 2022). However, the orientation of many pesantren is not environmentally oriented due to the strong traditional focus on social and political aspects (Malik, 2023) as well as the fiqh-oriented curriculum and Arabic language (Hardianto, 2019). However, this traditional focus has moved away from the more primordial focus of ritual-oriented education and mysticism. This change shows that pesantren have high adaptability in dealing with their environment (Isbah, 2020). This condition can open further changes in the future, especially in the orientation towards the environment.

While previous studies have acknowledged the environmental roles of pesantren, few have explored how spatial configuration directly contributes to measurable sustainability outcomes. This research seeks to address the existing gap by offering a quantitative approach that measures pesantren sustainability using satellite imagery and sustainability indices based on space utilization characteristics. The influence of pesantren in the environmental context is also felt in natural pesantren that are able to make contributions such as providing clean water in rural environments so that people no longer have to climb mountains to find water. Various optimal pesantren environmental engineering can be carried out to reduce the impact of global warming and help people protect the environment to prevent further damage to nature (Aulia et al, 2019; Nurkhin et al, 2023).

The ecopesantren program is one of the major programs of pesantren participation in preventing natural damage. The launching of the ecopesantren program was carried out on June 15, 2022 by the Center for Islamic Studies (PPI) of the National University. This program has also been presented in the arena of Conference of Parties (COP) 27, Global Climate Conference in Sharm El Shaikh, Egypt in November 2022. In August 2023, PPI UNAS held the first Massive Open Online Course (MMOC) which was attended by approximately 100 participants from Islamic boarding schools in Java and Sumatra. This MOOC agenda lasted for 1 month and consisted of 6 meetings to discuss various

opportunities and program implementations that were, will be, and have the potential to be carried out in the future to make massive environmental changes.

So far, no research has attempted to provide an overview of optimal actions for pesantren to carry out heat mitigation activities due to global climate change and local environmental damage. Previous research (Bakri, 2021) focused on only one pesantren and did not consider the diversity of pesantren types. This research aims to explore the diversity of pesantren across Indonesia using satellite imagery to analyze five types of spaces that influence environmental sustainability. This research seeks to provide encouragement for existing pesantren in Indonesia to mitigate climate change massively with optimal site engineering measures in accordance with the conditions of the pesantren. This method can be achieved by maximizing the Ecopesantren Sustainability Index (IKE) of the pesantren. The ecopesantren sustainability index (Saadiah, 2022) is a composite measurement tool that assesses the extent to which a pesankbartren integrates elements of environmental sustainability (A et al., 2023) in its land use, namely the proportion of white roof, green space, and blue space (Widyawati et al., 2024). In line with this intention, the purpose of this study is to measure the ecosystem sustainability index of pesantren and build a typology of pesantren based on space utilization characteristics in order to produce recommendations for improvement to increase the sustainability index. The existence of the ecopesantren sustainability index not only illustrates the competitiveness of each pesantren in competing for goodness, but also motivates pesantren to increasingly transform into ecopesantren optimally.

Research Method

A total of 46 pesantren registered in the Ecopesantren.com database were selected as the sample for this study. Although the program listed 48 members at the time of data collection (October 2023), two pesantren could not be identified in Google Earth satellite images and were excluded. For each of the remaining 46 pesantren, five types of land-use data were measured: (1) total land area, (2) white roof area (as a proxy for high-albedo, heat-reflective surfaces), (3) green space (areas with significant tree cover), (4) blue space (water bodies such as ponds), and (5) orange roof area (buildings with non-white roofs). The gray area was defined as the residual land after subtracting the other four, including open grounds such as fields and unshaded areas (Figure 1).

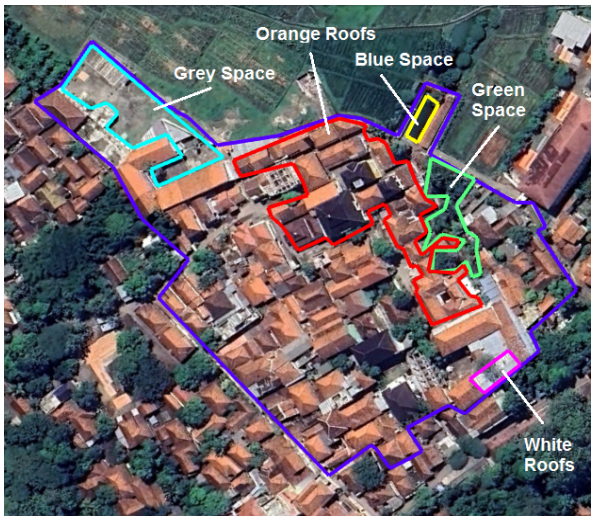


Figure 1. Example of Measurement Using Polygons on the Image of Pesantren Kempek Cirebon, Source: Google Earth, access date, October 5, 2023

Land measurements were conducted using the polygon tool in Google Earth Pro, with units in square meters. These five parameters were selected due to their direct

measurability from satellite imagery and their thermally significant surface characteristics in terms of urban heat island mitigation.

The data obtained was then used for the calculation of the sustainability index and hierarchical cluster analysis. Each parameter was calculated as a percentage of the total land area, following a standard proportional formula commonly used in spatial analysis (see Wu & Biljecki, 2021). However, satellite imagery may not fully capture recent land changes or canopy cover variations, and some spatial discrepancies may exist between satellite visuals and on-ground realities. This limitation was acknowledged in the interpretation of the results.

The area percentage score for each variable was normalized to a scale of 0 to 100, using the minimum and maximum values across the dataset. The pesantren with the highest relative percentage for a given parameter received a score of 100, and the rest were scaled proportionally. The sustainability index (Indeks Keberlanjutan Ekopesantren or IKE) was then calculated as the average of three component scores: white roof score, green space score, and blue space score.

Hierarchical cluster analysis was conducted to develop a typology of pesantren based on the five land-use proportions. This clustering approach is widely used to categorize spatial data into homogeneous groups. The Ward method was chosen for its efficiency in minimizing intra-cluster variance and producing distinct, interpretable clusters, which aligns with the objective of identifying spatial development patterns across pesantren (Zolfaghari et al., 2019).

Result and Discussion

The data obtained shows a very large variation in the size of the pesantren sample. Table 1 shows that the minimum size of a pesantren is 1,977 m2 or only 0.2 ha while the maximum reaches 211,298 m2 or 21 ha. This huge variation indicates that the average value cannot be relied upon to describe the size of the pesantren. In fact, the mean value of pesantren is 25,959 m2 while the standard deviation is even larger, namely 34,261 m2. It would be more descriptive to see the size of the pesantren based on a certain interval. Based on the interval, there are 12 pesantren with an area of 0.1 - 1 Ha, 33 pesantren with an area of 1 - 10 Ha, and one pesantren with an area above 10 Ha, namely Annuquyah Guluk Guluk pesantren in Madura, with an area of 21 Ha as mentioned above. The other two largest pesantren are Al Binaa at 9.8 Ha and Daarut Tauhid at 8.4 H

Table 1. Descriptive Statistics of Pesantren

Parameter	Minimum	Maksimum	Mean	Std. Deviation
Total area	1,977	211,298	25,959	34,261
Percentage of White Roof	0	16.06	3.84	3.24
Percentage of Green Land	0	54.31	16.19	11.63
Blue Land Percentage	0	7.69	0.62	1.61
Orange Roof Percentage	12.12	85.52	46.57	16.38
Percentage of Gray Land	7.26	73.72	32.76	14.39

The calculation results show that not all pesantren have white roofs, green fields, or blue fields. Four pesantren do not have white roofs, one pesantren does not have green land, and 35 pesantren do not have blue land. Thus, of the three types of sustainable land, water land is the least common land owned by pesantren. This is quite surprising because water is a very important element in Islamic teachings as a medium to clean themselves before praying. The absence of blue land may be due to the use of well water, rainwater, or tap water to fulfill hygiene needs rather than pond water. Some pesantrens are located near a large river so they can draw water from that source. The pesantren with the largest blue

land pesantren are Assalam Naga Beralih with a large pond at the back of the pesantren and Al Miftahul Huda Al Musri with several cultivation ponds scattered on various sides of the pesantren.

Although the mean values of the sustainable land variables (white, green, and blue) are all lower than the unsustainable land (orange and gray), there are pesantren that have a percentage of green roofs on more than half of the land. Pesantren Baburrasyad from South Aceh is the only pesantren with a green area above 50% at 54.31%. Pesantren Riyadhus Sholihin also has a sizable percentage of 43.29% green space to the total land area of the pesantren.

The number of pesantren that do not have green space, blue space, or white roof has an impact on the sustainability index value, which is a standardized average value of the percentage of the three spaces. In fact, there is no pesantren with a sustainability index of more than 50. The pesantren with the highest sustainability index are Al Miftahul Huda Al Musri with a sustainability index of 46.98 (white = 18.10; green = 44.30; blue = 78.56), Baburrasyad Al-Aziziyah with a sustainability index of 42.77 (white = 28.30; green = 100.00; blue = 0.00), and Darussalam Al Waliyyah Labuhan Haji with a sustainability index of 39.12 (white = 100.00; green = 17.36; blue = 0.00). The mean sustainability index was 20.63 (standard deviation 10.59) with a minimum value of 5.60.

To determine the typology of pesantren, a hierarchical cluster analysis was conducted with the input parameters of the percentage of white roof, green land, blue land, orange roof, and gray land. The results of the hierarchical cluster analysis are presented in Figure 2 below.

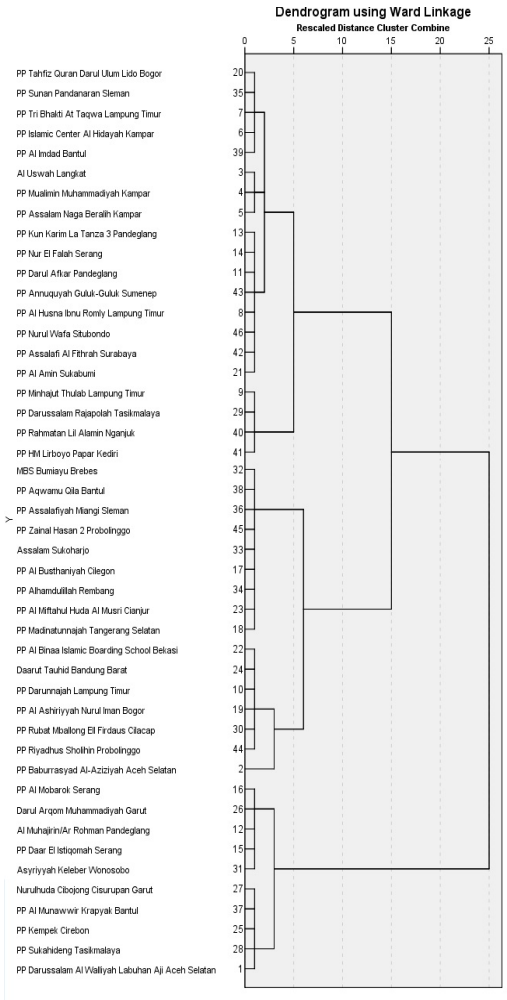


Figure 2. Dendrogram of Hierarchical Cluster Analysis Results

The number of clusters that can be synthesized from the above results depends on which cut-off point is taken. If 20 is used as the cut-off point, two clusters will be obtained, while if 15 is used, three clusters will be obtained. There is no exact method to determine how many clusters are optimal or which cut-off point can be used. Each context requires a different determination. More clusters means fewer cluster members and means a more individualized and less meaningful clustering process. On the other hand, the fewer clusters mean the simpler and more generalized and thus less sensitive to the different characteristics of the pesantren (McGuigan, 2010). Based on the consideration of these two sides, the researcher decided to divide the dendrogram of the analysis results into five clusters corresponding to the intersection point 4:

Cluster 1: Dense Pesantren

Dense pesantren are characterized by a very large orange space between 60-86%, while the green space is low (0-9%) and the gray space is 7-33%. Thus, the main characteristic of pesantren included in this cluster is the large number of buildings and is so dense that it leaves almost no green space and gray space. For example, PP Darussalam Al Waliyyah is a large pesantren with around 300 buildings. Some of these buildings have white roofs so the white space in this cluster is quite large, between 0-16%. The following table shows the members of the dense pesantren cluster while Figures 3 and 4 show examples of two members of this pesantren cluster, PP Darussalam Al Waliyyah and PP Sukahideng. The mean sustainability

The index of these pesantren is 14.25 with a range of 5.60 - 39.12.

Table 2. Members of the Dense Pesantren Cluster

ID	Pesantren	White Roof	Green Space	Blue Space	Orange Roof	Gray Space	IKE
16	PP Al Mobarok Serang	3	3	0	60	33	8.16
26	Darul Arqom Muhammadiyah Garut	3	1	0	63	33	6.69
12	Al Muhajirin/Ar Rohman Pandeglang	1	5	0	67	26	5.60
15	PP Daar El Istiqomah Serang	0	9	3	63	25	16.96
31	Asyriyyah Keleber Wonosobo	4	9	0	67	21	12.59
27	Nurulhuda Cibojong Cisurupan Garut	8	1	0	75	16	16.39
37	PP Al Munawwir Krapyak Brantul	2	1	0	79	17	5.97
25	PP Kempek Cirebon	4	8	1	77	10	16.01
28	PP Sukahideng Tasikmalaya	7	0	0	86	7	14.99
1	PP Darussalam Al Walliyah Labuhan Aji Aceh Selatan	16	9	0	66	9	39.12



Figure 3. PP Darussalam Al Walliyah (Dayah) Labuhan Aji South Aceh with 66% Orange Roofing. Source: Google Earth, access date, October 5, 2023.



Figure 4. Sukahideng Tasikmalaya PP with 86% Orange Roofing. Source: Google Earth, access date, October 5, 2023.

The characteristics of dense pesantren clusters make it difficult to implement tree planting because the remaining gray space is likely to be used for future development and building additions. Adding vegetation can be done by purchasing new land, however, the pesantren may become denser with buildings because there is no more land that can be purchased around the pesantren for expansion. A more likely solution is to utilize the roofs of the buildings as white roofs, green roofs, or solar roofs. White roofs need to be created during construction, making it less practical for buildings that have already been erected. Green roofs are a cheap solution and can involve all santri (students) and ustad (teachers) by planting the roof with vegetation. Solar roofing solutions are more costly but can support energy independence and the use of sustainable green energy from sunlight. In addition, the price of solar panels is getting cheaper year by year, allowing massive use on the roofs of pesantren. The blue roof solution by creating a pond on the flat roof of the pesantren can also increase evaporation as well as a fishery medium that can be tried.

Cluster 2: Green Pesantren

The second cluster is characterized by the high percentage of green space owned by its members. A total of seven pesantren in this cluster have a proportion of green space between 27-54%. Pesantren Baburrasyad Al-Aziziyah South Aceh is the greenest pesantren

with a percentage of green space of more than 50%. Pesantren Darut Tauhid West Bandung is also a green pesantren with a percentage of 27%. The space proportions of the green pesantren can be seen in the following table. The sustainability index is in the range of 25.83 - 42.77 with an average of 31.25, which is certainly much higher than the previous cluster of only 14.25.

Table 3. Green Pesantren Cluster Members

ID	Pesantren	White Roof	Green Space	Blue Space	Orange Roof	Gray Space	IKE
22	PP Al Binaa Islamic Boarding School Bekasi	5	27	0	36	32	28.73
24	Daarut Tauhid Bandung Barat	5	27	0	32	36	25.83
10	PP Darunnajah Lampung Timur	4	30	0	41	25	26.71
19	PP Al Ashiriyyah Nurul Iman Bogor	4	32	0	38	25	28.83
30	PP Rubat Mballong Ell Firdaus Cilacap	3	34	2	33	28	37.93
44	PP Riyadhus Sholihin Probolinggo	1	43	0	32	24	27.79
2	PP Baburrasyad Al-Aziziyah Aceh Selatan	5	54	0	12	29	42.77



Figure 5. PP Baburrasyad Al-Aziziyah South Aceh with 54% Green Space. Source: Google Earth, access date, October 5, 2023.



Figure 6. PP Riyadhus Sholihin Probolinggo with 43% Green Space. Source: Google Earth, access date, October 5, 2023.

Green pesantren no longer have the challenge of greening the site. The ability of pesantren to maintain and increase green space can be seen as an enviable achievement by other pesantren. The next step of progress that needs to be achieved by green pesantren is to utilize the green space for increasing biodiversity, both fauna and flora diversity. Its utilization as a recreational space for the surrounding community, especially for pesantren in urban areas, can also be an option but with a note on the need for maintenance to maintain and even improve the quality of the green space. This step can be achieved by utilizing the entrance fee as a maintenance fee.

Cluster 3: Pesantren with Space Competition

The third cluster is filled by pesantrens with a relatively balanced proportion of space. The orange space is about twice the size of the green space as well as the gray space. The nine pesantren in this category have a range of green space between 12-28%, orange space between 46-58% and gray space between 16-29%. This type of pesantren is said to be a pesantren with space competition because it can be seen that half of the pesantren space is in a position between being retained or not as green space. The gray space can become the land for the establishment of new buildings while the green space can be converted into gray space to prepare for the next buildings. The average sustainability index of pesantren in this cluster is 26.48 with a range between 13.71-46.98.

Table 4. Members of the Pesantren Cluster with Space Competition

ID	Pesantren	White Roof	Green Space	Blue Space	Orange Roof	Gray Space	IKE
32	MBS Bumiayu Brebes	9	12	0	54	26	24.99
38	PP Aqwamu Qila Bantul	9	17	0	55	19	29.36
36	PP Assalafiyah Miangi Sleman	2	19	5	50	24	35.67
45	PP Zainal Hasan 2 Probolinggo	1	20	0	50	29	13.71
33	Assalam Sukoharjo	3	25	0	46	26	21.40
17	PP Al Busthaniyah Cilegon	2	26	1	51	20	26.75
34	PP Alhamdulillah Rembang	2	28	0	51	19	21.96
23	PP Al Miftahul Huda Al Musri Cianjur	3	24	6	50	17	46.98
18	PP Madinatunnajah Tangerang Selatan	1	25	0	58	16	17.52

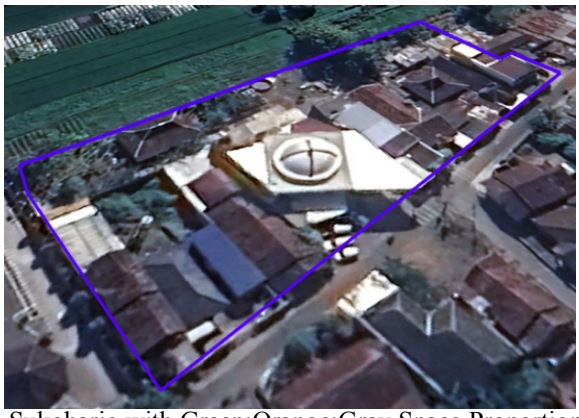


Figure 7. PP Assalam Sukoharjo with Green:Orange:Gray Space Proportion 25:46:26. **Source: Google Earth, access date, October 5, 2023.**



Figure 8. PP Aqwamu Qila Bantul with Green:Orange:Gray Space Proportion 17:55:19**, Source: Google Earth, access date, October 5, 2023.**

An appropriate sustainable solution for pesantren with this type of space competition is to implement balanced development. Every new development must be accompanied by greening efforts and development needs to be carried out by utilizing gray space. This makes the proportion of green space and orange space increase in harmony as the gray space decreases. Of course, if the pesantren has no development plans soon, the gray space needs to be converted into green or blue space to increase the sustainability index of the pesantren site.

Cluster 4: Pesantren Towards Development

Pesantren in this category are said to be heading towards development because the pesantren land is dominated by gray space. The presence of a large amount of gray space indicates the preparation of land for development, although it can also mean the occurrence of drought problems. There are only four pesantren in this category, including Lirboyo (74%), Rahmatan lil Alamin (47%), Darussalam Rajapolah (57%), and Minhajut Thulab (60%). In line with the dominance of gray space, green and orange space are relatively balanced where green space exists in the range of 4-17% and orange space in the range of 19-24%. The Ecopesantren Sustainability Index (IKE) of the pesantren cluster towards development ranges from 6.93 - 34.92, with an average sustainability index of 20.45.

Table 5. Members of the Pesantren Towards Development Cluster

ID	Pesantren	White Roof	Green Space	Blue Space	Orange Roof	Gray Space	IKE
9	PP Minhajut Thulab Lampung Timur	0	15	0	24	60	9.46
29	PP Darussalam Rajapolah Tasikmalaya	9	14	1	19	57	30.47
40	PP Rahmatan Lil Alamin Nganjuk	12	17	0	24	47	34.92
41	PP HM Lirboyo Papar Kediri	2	4	0	20	74	6.93



Figure 9. HM PP Lirboyo Papar Kediri with 74% Gray Room. Source: Google Earth, access date, October 5, 2023.



Figure 10. PP Minhajut Thulab East Lampung with 60% Gray Room. Source: Google Earth, access date, October 5, 2023.

The sustainability solution in the situation faced by the pesantren towards development is to increase the proportion of green and blue spaces. Excess gray land should be conserved to provide ecological benefits for both the pesantren residents and the surrounding community. This conversion is quite easy and not costly. New buildings can be erected strategically between green spaces or separated in different blocks with green spaces.

Cluster 5: Built-up Pesantren

Cluster 5 is the cluster with the most members. A total of 16 remaining pesantren are in this cluster. The developed pesantren are relatively stable, characterized by a balanced proportion of orange space to gray space while the green space is relatively small. Orange space in this group ranges from 31-52% while gray space ranges from 32-57%. Green spaces are in the range of only 2-21%. Boarding schools in this category are likely to have completed all essential building construction complemented by functional gray spaces such as parking lots and sports fields (including grass fields). The sustainability index of members of this cluster is in the range of 9.61-35.48 with an average of 16.72. This index is the second lowest, above the cluster of dense pesantren (Cluster 1, IK = 14.25).

Table 6. Members of the Established Pesantren Cluster

ID	Pesantren	White Roof	Green Space	Blue Space	Orange Roof	Gray Space	IKE
20	PP Tahfiz Quran Darul Ulum Lido Bogor	0	16	0	38	47	9.75
35	PP Sunan Pandanaran Sleman	0	16	0	37	47	9.61
7	PP Tri Bhakti At Taqwa Lampung Timur	5	12	0	37	46	17.78
6	PP Islamic Center Al Hidayah Kampar	5	21	1	33	41	27.47
39	PP Al Imdad Bantul	3	21	0	31	44	19.66
3	Al Uswah Langkat	8	2	0	43	48	17.57
4	PP Mualimin Muhammadiyah Kampar	3	6	1	41	50	12.18
5	PP Assalam Naga Beralih Kampar	0	3	8	32	57	35.48
13	PP Kun Karim La Tanza 3 Pandeglang	2	18	0	42	38	15.80
14	PP Nur El Falah Serang	6	15	0	42	37	21.39
11	PP Darul Afkar Pandeglang	5	18	0	45	32	20.89
43	PP Annuquyah Guluk-Guluk Sumenep	1	21	0	44	34	14.71
8	PP Al Husna Ibnu Romly Lampung Timur	2	10	0	48	39	10.51
46	PP Nurul Wafa Situbondo	3	10	0	48	39	12.57
42	PP Assalafi Al Fithrah Surabaya	4	5	0	49	43	10.63
21	PP Al Amin Sukabumi	2	12	0	52	34	11.82



Figure 11. PP Kun Karim La Tanza 3 Pandeglang with Orange:Gray Proportions 42:38



Figure 12. PP Al Uswah Langkat with Orange:Gray Proportions 43:48. Source: Google Earth, access date, October 5, 2023.

The solution for built-up pesantren to be sustainable from the site aspect is to add vegetation so as to expand the green space. The small amount of green space in these pesantren suggests that development still pays little attention to environmental aspects. Although they may appear modern, the lack of vegetation creates an arid impression. Non-functional gray areas can be selectively converted into green zones, and building rooftops offer potential for installing solar panels, green roofs, or reflective materials.

These recommendations align with findings from Wu and Biljecki (2021), who emphasized the significant role of reflective surfaces and green coverage in enhancing urban sustainability. Likewise, Gu and You (2022) showed that green and blue infrastructure are strong predictors of spatial resilience. The low sustainability index observed in pesantren reflects similar patterns, where limited surface diversity contributes to environmental vulnerability.

Comparison with Previous Studies

Compared to earlier studies, such as Bakri (2021) who analyzed a single pesantren without spatial differentiation, this study provides a more comprehensive overview using spatial clustering. While Bakri's findings were largely qualitative, this research quantitatively confirms the challenges in balancing built and natural elements in pesantren environments. Moreover, the typology developed here offers practical classifications that can inform future green pesantren development strategies.

Conclusion

This research introduces the Ecopesantren Sustainability Index (IKE), a new concept for assessing pesantren sustainability by quantifying land use performance based on the proportion of white roofs, green spaces, and blue areas, while also serving to evaluate spatial configurations and classify pesantren typologies that contribute to ecological sustainability.

The results show that the average IKE among member pesantren in the ecopesantren program remains below 50, primarily due to the limited presence of blue spaces and white roofs. This indicates that most pesantren have not yet adopted a diverse set of strategies to mitigate local heat. Therefore, targeted improvements are essential to expand

environmentally functional land use. This highlights the urgency for broader adoption of blue and white infrastructure to enhance environmental performance and reduce thermal vulnerability.

Moreover, the study reveals a considerable variation in spatial patterns across pesantren. Cluster analysis identified five typologies: dense pesantren, green pesantren, pesantren with space competition, pesantren towards development, and built-up pesantren. When arranged by average IKE, the clusters rank from lowest to highest as follows: dense (14.25), built-up (16.72), towards development (20.45), space competition (26.48), and green (31.25). The absence of clusters dominated by blue or white features further confirms the imbalance in current spatial approaches.

Based on these findings, the study provides actionable recommendations tailored to each cluster type, aiming to enhance sustainability through strategic land conversion and integration of green technologies. These insights offer practical value not only for the advancement of the ecopesantren program but also for broader ecological restoration efforts initiated by Islamic educational institutions. To this end, policymakers and pesantren administrators should prioritize the expansion of green and blue infrastructure, while also supporting renewable energy initiatives such as solar roofing and green roofs.

This study acknowledges its descriptive nature as a limitation. Future research should empirically examine the thermal effects of different surface types in pesantren environments, validating the role of white, green, and blue spaces in reducing heat stress. Quantitative studies are also needed to evaluate the financial feasibility of green investment models for ecopesantren. Additionally, in-depth architectural case studies and regression-based spatial analyses could deepen our understanding of how land use composition influences microclimate moderation.

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