Analysis of Connectivity and Accessibility Improvement of Bandung Public Transportation Network Using Graph Theory

Transformation of Angkot Routes into Feeder Services Based on Maximum Coverage

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***Abstract*— Public transportation accessibility in Bandung remains limited despite the existence of formal services and conventional angkot routes. This study proposes a graph-based framework for transforming angkot services into feeder routes integrated with the existing transportation network. The formal network is modeled as a graph whose vertices represent stops and edges represent direct connections. Uncovered stops are identified through gap analysis and reduced to eliminate redundancy. Candidate feeder hubs are then selected using the Maximum Coverage Problem solved by a greedy algorithm, followed by spatial expansion and route construction based on the nearest-neighbor heuristic. The resulting feeder routes are projected onto the actual road network obtained from OpenStreetMap. Network performance is evaluated using several graph metrics, including average degree, articulation points, bridges, and diameter. The proposed network achieves a coverage ratio of 83.71%, exceeding the 62.02% coverage provided by the existing angkot network while requiring fewer routes. Compared with the existing formal transportation network, the proposed network increases connectivity, reduces articulation points and bridges, and shortens the network diameter. These results indicate that transforming conventional angkot routes into feeder services can improve accessibility and structural robustness while maintaining operational efficiency.**

Keywords*— *graph theory, public transportation, feeder routes, maximum coverage problem, network connectivity.

I. Introduction

Public transportation plays an important role in supporting urban mobility and accessibility. In Bandung, angkot (public minibus) has historically served as one of the most extensive transportation modes due to its flexible routes and broad spatial coverage. However, its competitiveness and service quality have gradually declined, while the increasing popularity of private vehicles and ride-hailing services has reduced its attractiveness [1]. Previous studies also indicate that the current form of angkot is unlikely to remain competitive in the future and therefore requires transformation into a more reliable public transport system [2].

To improve urban mobility, the Bandung City Government has expanded formal public transportation services and proposed the transformation of conventional angkot into feeder services integrated with the existing network [3]. Similar initiatives have also been implemented in the Greater Bandung region through the Metro Jabar Trans feeder system, which utilizes existing angkot fleets as part of a modern and integrated public transportation system [4]. Despite these efforts, several areas remain underserved, resulting in first-mile and last-mile accessibility issues.

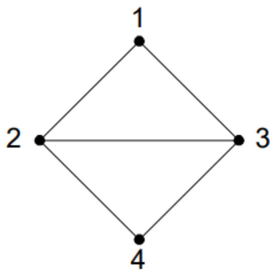
Instead of eliminating angkot services entirely, transforming existing angkot routes into formal feeder services provides an opportunity to preserve their extensive coverage while enhancing integration with the main transit corridors. From the perspective of graph theory, a transportation network can be represented as a graph, where vertices denote stops and edges represent direct connections between them. Such a representation enables connectivity and accessibility to be analyzed quantitatively through graph metrics.

Therefore, this study proposes a graph-based transformation of angkot routes into formal feeder services for the Bandung public transportation network. Candidate feeder hubs are selected using the Maximum Coverage Problem solved by a greedy algorithm, followed by spatial expansion and route construction procedures to generate operational feeder routes. The resulting network is then evaluated through connectivity analysis and compared with the existing network to assess its effectiveness in improving accessibility and network robustness.

II. Theoretical Framework

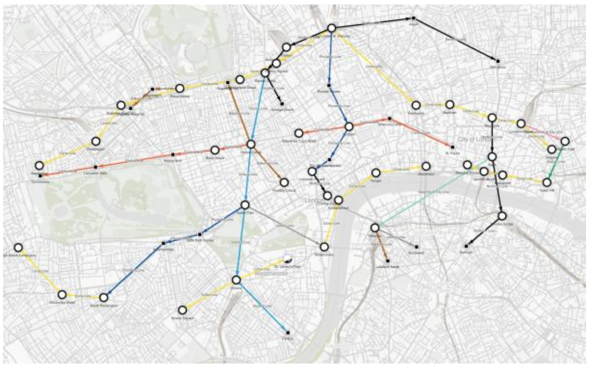
A. Graph

Graph theory provides a mathematical framework for representing discrete objects and the relationships between them. A graph G is defined as $G = (V, E)$, where V is a non-empty set of vertices $V = \{v_1, v_2, \ldots, v_n\}$, and E is a set of edges connecting pairs of vertices $E = \{e_1, e_2, \ldots, e_n\}$.



The vertex set V cannot be empty, implying that a graph must contain at least one vertex. In contrast, the edge set E may be empty, indicating that a graph may consist solely of isolated vertices without any connections.

In the context of public transportation networks, vertices represent bus stops, terminals, or stations, while edges represent direct route segments connecting two stops. Therefore, a transportation network can be modeled as a graph $G = (V, E)$, enabling its topological properties to be analyzed mathematically.



B. Network Metrics

Several network metrics are employed to evaluate the connectivity, accessibility, and structural robustness of transportation networks. These metrics provide quantitative measures of the network structure and are widely used in graph-theoretic analyses

1) Connected Components

A connected component is defined as a subset of vertices in which every pair of vertices is connected by at least one path. A graph containing a single connected component indicates that all nodes are mutually reachable, whereas multiple connected components imply disconnected subnetworks [5].

The number of connected components is commonly used to evaluate the overall connectivity of a transportation network. Fewer components generally indicate better accessibility and integration among network elements.

2) Average Degree

The average degree represents the average number of edges connected to each vertex and is defined as

$$\bar{k} = \frac{2 \mid E \mid}{\mid V \mid}$$

where $\mid V \mid$ and $\mid E \mid$ denote the numbers of vertices and edges, respectively [5].

The average degree reflects the density of the network. A larger average degree generally implies the existence of more alternative paths and stronger connectivity among nodes

3) Diameter

The graph diameter is defined as the maximum shortest-path distance between any two vertices,

$$D(G) = \max_{u,v \in V} d(u, v)$$

where $d(u, v)$ denotes the shortest-path distance between vertices u and v[5].

Diameter is frequently used to assess accessibility and efficiency in transportation systems. Smaller diameters indicate that destinations can be reached through fewer intermediate stops and shorter paths.

4) Articulation Points

An articulation point is a vertex whose removal increases the number of connected components in the graph. Formally, a vertex $v \in V$ is an articulation point if

$$c(G - v) > c(G)$$

where $c(G)$ denotes the number of connected components [5].

Articulation points represent critical nodes whose failure may fragment the network. Therefore, they are widely used to evaluate network vulnerability and structural robustness.

5) Bridges

An articulation point is a vertex whose removal increases the number of connected components in the graph. Formally, a vertex $v \in V$ is an articulation point if

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C. Maximum Coverage Problem

The Maximum Coverage Problem (MCP) is a combinatorial optimization problem that aims to maximize the number of covered elements by selecting a limited number of subsets from a collection of candidates [6]. Owing to its ability to maximize service coverage under resource constraints, MCP has been widely applied in facility location and transportation network optimization problems [7]. Let

$$U = \{u_1, u_2, \ldots, u_n\}$$

denote the set of uncovered stops, and let

$$S = \{S_1, S_2, \ldots, S_m\}$$

represent the collection of candidate subsets, where each subset $S_j \subseteq U$ contains the uncovered stops that can be served by candidate hub j. The objective of MCP is to determine a set of selected hubs

$$K \subseteq \{1,2,\ldots,m\}$$

that maximizes the number of covered stops. Formally,

$$\max \left| \bigcup_{i \in K} S_i \right|$$

subject to

$$|K| = k$$

where k denotes the predetermined number of hubs. The objective function maximizes the total number of covered stops, while the constraint limits the number of selected hubs.

In this study, the set U corresponds to uncovered public transportation stops identified through gap analysis, whereas each subset S_j represents the stops located within the service radius of candidate hub j. The MCP framework is subsequently used to determine feeder hub locations that maximize accessibility coverage.

One of the most commonly used approaches for solving MCP is the greedy algorithm. Starting from an empty solution, the algorithm iteratively selects the candidate hub that contributes the largest number of previously uncovered stops until the specified number of hubs is reached. In this study, a greedy algorithm is employed to iteratively select candidate hubs that provide the largest number of newly covered stops.

D. Spatial Expansion and Feeder Route Construction

After the candidate hubs are selected through the Maximum Coverage Problem, the service area is expanded by incorporating neighboring gap stops within a predefined spatial threshold. Let H denote the set of selected hubs and G denote the set of uncovered stops. A gap stop g_j is directly covered by a hub h_i if

$$d(h_i, g_j) \le r_h,$$

where $d(\mathrm{x},\mathrm{y})$ represents the geographical distance and r_h denotes the hub coverage radius. Furthermore, uncovered stops can be incorporated through spatial expansion if they are located within a distance r_g from an already covered stop, i.e.,

$$d(g_i, g_j) \le r_g.$$

This process is performed iteratively until no additional gap stops can be included. Consequently, the effective service area of each hub extends beyond its direct coverage radius and enables broader accessibility to previously underserved regions.

To reduce excessive route overlap while maintaining alternative access paths, each covered stop is associated with its two nearest hubs whenever possible. This controlled redundancy improves connectivity and provides additional feeder connections without introducing excessive duplication of routes.

Subsequently, the stops assigned to each hub are ordered using the nearest-neighbor heuristic. Starting from the hub location, the next stop is selected as the nearest unvisited stop, which can be expressed as

$$g_{\text{next}} = \arg\min_{g \in U} d(g_{\text{current}}, g),$$

where U denotes the set of unvisited stops. This procedure is repeated until all assigned stops have been visited. The nearest-neighbor heuristic is widely used in routing problems because of its simplicity and computational efficiency [8].

To maintain operational feasibility and improve route compactness, excessively long routes are partitioned into multiple feeder sub-routes. Each route starts and terminates at its corresponding hub, thereby ensuring direct integration with the existing formal public transportation network.

Finally, the generated feeder routes are projected onto the actual road network obtained from OpenStreetMap (OSM). Geographic Information Systems (GIS) are subsequently employed to visualize the resulting network and provide a realistic representation of the proposed feeder system. The resulting network is then evaluated using graph-theoretic metrics to assess connectivity, accessibility, and structural robustness.

III. Methodology

A. Data Collection and Preprocessing

The formal public transportation network data were obtained from OpenStreetMap (OSM), which provides geographical information regarding bus stops and route segments. The transportation network was modeled as a graph $G = (V, E)$, where vertices represent stops and edges represent direct connections between consecutive stops.

Since the initial dataset contains nodes located outside the administrative boundary of Bandung, a filtering process was performed to retain only nodes and edges within the study area. Subsequently, stops that were not connected to the formal transportation network were identified as gap stops. These stops represent areas with limited accessibility and constitute potential targets for feeder services.

To reduce redundancy and avoid excessive node density, nearby gap stops were consolidated through a gap reduction process. As a result, multiple stops located within close proximity were represented by a single node, producing a more compact and computationally efficient network representation.

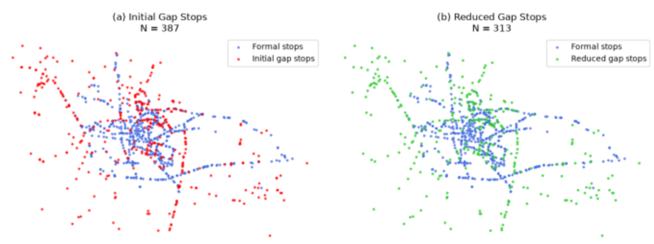

FIGURE 1: Comparison of the initial and reduced gap-stop distributions with respect to the existing formal transportation network.

Figure 1 illustrates the distribution of the initial and reduced gap stops relative to the existing formal transportation network. The reduction process decreases the number of gap nodes from 387 to 313 by eliminating closely located and redundant stops.

Consequently, the resulting gap-stop distribution becomes more compact and computationally manageable while preserving the overall spatial pattern of underserved regions.

B. Candidate Set Generation and Maximum Coverage

Candidate sets were generated for each formal stop to determine the set of gap stops that could potentially be served. A gap stop g_j is considered directly reachable from a hub h_i if the geographical distance between them satisfies

$$d(h_i, g_j) \leq r_h,$$

where r_h denotes the hub radius. In this study, a hub radius of 1000 m was adopted.

To further increase service coverage, spatial expansion was applied to neighboring gap stops. A gap stop g_j was included in the candidate set if its distance to an already covered gap stop g_i satisfied

$$d(g_i, g_j) \leq r_g,$$

where r_g denotes the gap radius. In this study, a gap expansion radius of $r_g = 750$ was applied, allowing neighboring gap stops within 750 m of an already covered gap stop to be iteratively incorporated into the candidate set. The expansion process was repeated iteratively until no additional gap stops could be added.

After generating the candidate sets, the Maximum Coverage Problem was solved using a greedy algorithm. Starting from an empty solution, the algorithm iteratively selected the hub providing the largest number of newly covered gap stops. The process was repeated until the predetermined number of hubs was reached. In this study, the number of selected hubs was fixed at $k = 20$.

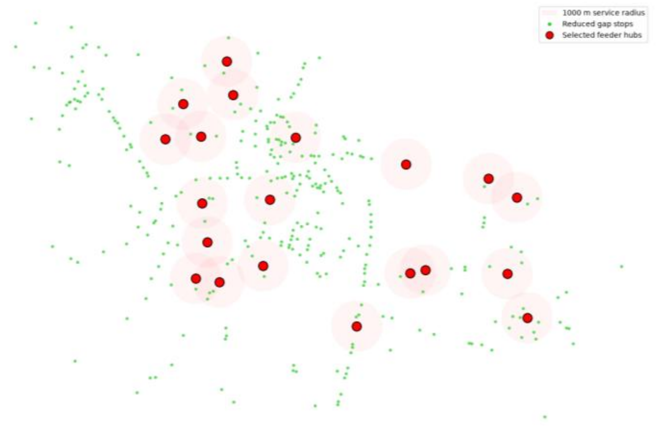

FIGURE 2: SELECTED FEEDER HUBS AND THEIR 1 KM SERVICE COVERAGE AREA

C. Feeder Route Construction

After the feeder hubs are selected, the covered gap stops are assigned to their nearest hubs to eliminate excessive overlap and produce mutually exclusive service regions. Consequently, each stop is associated with a unique hub, resulting in compact feeder service areas and reducing route redundancy. Figure 3 illustrates the spatial assignment of covered stops to their corresponding feeder hubs.

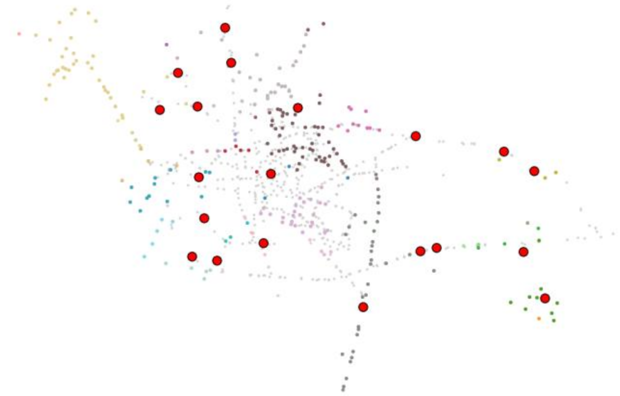

FIGURE 3: ASSIGNMENT OF COVERED GAP STOPS TO THE SELECTED FEEDER HUBS.

For each hub, the sequence of stops is determined using the nearest-neighbor heuristic. Starting from the hub location, the algorithm iteratively selects the nearest unvisited stop until all assigned stops have been traversed. This approach provides a computationally efficient approximation for route ordering while maintaining geographical continuity among successive stops.

Since some hubs serve relatively large numbers of stops, excessively long routes are partitioned into multiple sub-routes to improve operational feasibility. The splitting process aims to maintain balanced route lengths while preserving the spatial coherence of each route.

Finally, the ordered stops are projected onto the actual road network obtained from OpenStreetMap (OSM). Shortest paths between consecutive stops are computed to generate realistic feeder routes that follow existing road segments instead of straight-line connections. Geographic Information Systems (GIS) are subsequently employed to visualize the resulting feeder network. Figure 4 presents the final feeder routes projected onto the road network of Bandung.

D. Network Analysis and Visualization

To evaluate the impact of the proposed feeder network, a proposed graph was constructed by integrating the formal transportation network with the generated feeder routes. Several graph metrics were then computed to assess the structural characteristics of the network, including the number of connected components, average degree, articulation points, bridges, and network diameter. These metrics provide insights into the connectivity and robustness of the transportation network. Furthermore, Geographic Information Systems (GIS) were employed to visualize the resulting routes and facilitate spatial interpretation of the proposed network.

IV. RESULT

A. Existing Network Characteristics

TABLE 1
GRAPH METRICS OF THE EXISTING TRANSPORTATION NETWORK

Metrics	***Existing Network***
Nodes	542
Edges	658
Average Degree	2.428
Articulation Points	52
Bridges	52
Diameter	47

The existing transportation network (DAMRI & MJT & TMB) consists of 542 nodes and 658 edges, forming a single connected component without isolated nodes. The average degree is 2.428, indicating that most stops are connected to only a few neighboring stops. Furthermore, 52 articulation points and 52 bridges were identified, suggesting that several critical stops and links play a significant role in maintaining overall connectivity. The network diameter of 47 indicates the maximum shortest-path distance between any two stops in the largest connected component.

B. Existing Angkot Coverage

TABLE 2
EXISTING ANGKOT COVERAGE

Metrics	***Existing Angkot Network***
Nodes	387
Covered Nodes	240
Coverage Ratio	62.02%
Number of Routes	37

Based on OpenStreetMap data, the existing angkot network consists of 37 routes and covers 240 out of 387 identified gap nodes, resulting in a coverage ratio of 62.02%.

C. Hub Selection and Coverage Analysis

TABLE 3
PROPOSED FEEDER COVERAGE

Metrics	***Existing Network***
Reduced Gap Nodes	313
Covered Gap Nodes	262
Coverage Ratio	83.71%
Number of Routes	30

Compared with the existing angkot network, the proposed feeder system provides substantially higher spatial coverage despite using fewer routes. Specifically, the coverage ratio increases from 62.02% to 83.71%, corresponding to an improvement of approximately 21.69 percentage points. This result indicates that the transformation of conventional angkot into feeder services enables a more efficient utilization of routes while extending accessibility to previously underserved areas. Moreover, the reduced number of routes suggests that route overlap can be minimized without sacrificing coverage performance.

The proposed feeder network was constructed using the Maximum Coverage Problem solved by a greedy algorithm. After the gap reduction process, 313 gap nodes were identified as candidate service locations. By selecting 20 feeder hubs and applying spatial expansion, 262 gap nodes were successfully covered, resulting in a coverage ratio of 83.71%. Furthermore, the route construction process generated 30 operational feeder routes. Compared with the existing angkot network, the proposed feeder system achieves higher spatial coverage with fewer routes, indicating a more efficient utilization of the transportation network.

Compared with the existing angkot network, which consists of 37 routes and covers 240 gap nodes, the proposed feeder network achieves a higher coverage ratio of 83.71% while requiring only 30 feeder routes. This result suggests that transforming conventional angkot services into feeder routes can improve accessibility while reducing route redundancy.

D. Comparison with Existing Formal Network

TABLE 4
STRUCTURAL COMPARISON BETWEEN EXISTING FORMAL AND PROPOSED NETWORK

Metrics	***Existing Formal Network***	***Proposed Network***
Nodes	542	803
Edges	658	1059
Average Degree	2.428	2.638
Articulation Points	52	28
Bridges	52	28
Diameter	47	34

Table 4 presents the structural comparison between the existing formal public transportation network and the proposed integrated network. The proposed network increases the number of nodes and edges while improving overall connectivity. The average degree rises from 2.428 to 2.638, indicating a denser network. Furthermore, the number of articulation points and bridges decreases from 52 to 28, suggesting improved structural robustness. The diameter also decreases from 47 to 34, implying shorter travel paths across the network.

E. Comparison with Existing Integrated Network

TABLE 5
STRUCTURAL COMPARISON BETWEEN INTEGRATED NETWORK AND PROPOSED NETWORK

Metrics	***Existing Integrated Network***	***Proposed Network***
Nodes	784	803
Edges	1190	1059
Average Degree	3.036	2.638
Articulation Points	7	28
Bridges	7	28
Diameter	29	34

Table 5 compares the proposed feeder network with the existing integrated network composed of formal public transportation services and conventional angkot routes. The existing integrated network exhibits fewer articulation points, fewer bridges, and a smaller diameter because the extensive overlap among angkot routes creates a highly redundant network structure. Previous studies have shown that path redundancy and route diversity improve network resilience by providing alternative paths under disruptions [9], [10].

However, excessive redundancy may also reduce operational efficiency because multiple routes serve similar corridors and increase operational complexity. Transportation systems generally involve a trade-off between robustness and efficiency, where additional redundancy improves resilience but may increase overlap and resource requirements [10]. Therefore, the proposed network adopts a controlled redundancy strategy through the two-nearest-hub assignment mechanism. Although the proposed network has more articulation points and a slightly larger diameter than the existing integrated network, it achieves higher coverage while maintaining sufficient structural robustness with fewer overlapping services. These results suggest that the proposed feeder network provides a more balanced trade-off between robustness and operational efficiency.

F. Visualization of Proposed Feeder Route

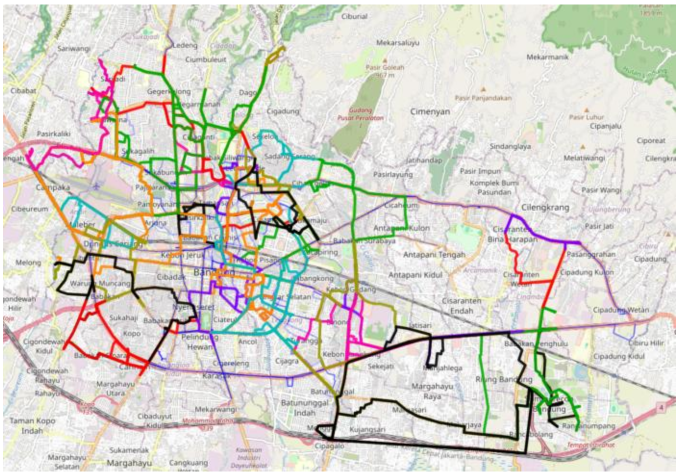

FIGURE 4: PROPOSED FEEDER ROUTES PROJECTED ONTO THE BANDUNG ROAD NETWORK.

Figures 4 illustrates the spatial distribution of the proposed feeder routes generated from the selected hub locations. The routes extend from major transportation hubs toward previously underserved areas and provide connections between gap stops and the formal public transportation network. The resulting network achieves broader spatial coverage while maintaining connectivity through multiple feeder corridors.

V. CONCLUSION

This study proposed a framework for transforming conventional angkot services into an integrated feeder system to improve the accessibility and connectivity of Bandung's public transportation network using graph theory and the Maximum Coverage Problem. A total of 387 uncovered stops were identified from the existing formal network, and 20 feeder hubs were selected to maximize coverage. The proposed feeder routes achieved a coverage ratio of 83.71%, exceeding the 62.02% coverage provided by the existing angkot network.

Compared with the existing formal network, the proposed network increased the number of nodes and edges while improving structural connectivity. The average degree increased from 2.428 to 2.638, whereas the number of articulation points and bridges decreased from 52 to 28. In addition, the network diameter was reduced from 47 to 34, indicating shorter paths and improved accessibility across the network. Although the existing integrated network exhibits higher redundancy due to extensive route overlap, the proposed network provides a better balance between structural robustness and operational efficiency through a controlled redundancy strategy.

These findings demonstrate that transforming conventional angkot services into an official feeder system can improve network coverage and connectivity while maintaining adequate robustness. Future work may incorporate passenger demand, travel time, route capacity, and multi-objective optimization to further enhance feeder route design and evaluate network resilience under disruption scenarios.

Several limitations should be noted. The analysis relies on publicly available OpenStreetMap data and focuses primarily on graph connectivity and coverage. Consequently, passenger demand, travel time, service frequency, operational costs, and transfer penalties are not explicitly considered. Moreover, the route generation process employs heuristic approaches and may not yield globally optimal solutions. Future work may incorporate demand-based data and multi-objective optimization to produce more realistic feeder routes and evaluate network performance under disruption scenarios.

VIDEO LINK AT YOUTUBE

ristek.link/videoMatdisRendy

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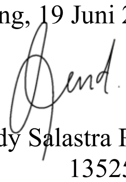
PERNYATAAN

Dengan ini saya menyatakan bahwa makalah yang saya tulis ini adalah tulisan saya sendiri, bukan saduran, atau terjemahan dari makalah orang lain, dan bukan plagiasi.

Bandung, 19 Juni 2026



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