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Optimizing Solar Panel Efficiency: Integration of Dual Axis Solar Tracking and Reflectors

Alvin Rinaldi Wiharja[1], Levin Halim[1], Faisal Wahab[1]

[1] Department of Electrical Engineering, Faculty of Industrial Technology, Parahyangan Catholic University, Bandung, Jawa Barat 40141, Indonesia

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Corresponding Author: Levin Halim (email: halimlevin@unpar.ac.id)

ABSTRACT — Solar panels have relatively low efficiency, but their performance can be enhanced by a tracking system directing the panels perpendicular to the light source and adding reflectors to capture more sunlight. The dual-axis solar tracking method, using two linear actuators and optimized by fuzzy logic, efficiently positions solar panels for maximum sunlight exposure. This research aimed to improve the overall efficiency of solar panels by integrating reflectors with a dual-axis solar tracking system optimized by fuzzy logic. Specifically, this research tested various reflectors to determine the most significant efficiency improvement. This research consisted of two tests: a tracking test and a reflector test using a halogen lamp. The tracking test was conducted by positioning the light in four different positions. The light sensor data were obtained before and after the solar tracking, indicating that the tracking was successful. All these tests were conducted with the light source radiation of 1,168 W/m2. This research concluded that the tracking system effectively positioned the solar panels toward the light source, with the tracking time ranging from 12 to 16 s, depending on the position. Aluminum foil is the most cost-effective reflector, priced at IDR5,341 per 1% increase in efficiency, compared to mirrors at IDR20,204 per 1% and reflective tape at IDR48,034 per 1%. In conclusion, the integration of aluminum foil reflectors and a dual-axis solar tracking system, optimized by fuzzy logic, significantly improves the efficiency of solar panels, which is both cost-effective and efficient.

KEYWORDS — Cost-Effectiveness, Dual-Axis Solar Tracking, Fuzzy Logic, Reflectors, Solar Panel Efficiency.

I. INTRODUCTION

With the development of civilization, energy consumption continues to increase [1]. More energy will be needed shortly to maintain the flow of human development. The leading solution is to burn more fossil fuels [2]. However, fossil fuel availability is currently decreasing [3]. This causes the price of these resources to increase [4]. In addition, fossil fuel combustion is not environmentally friendly since it will cause a lot of pollution. Therefore, new energy sources that are environmentally friendly and continuously renewable are needed [5]. Renewable energy solves the problem of limited fossil energy and can reduce pollution [6]. Renewable energy is produced using natural sources and will run out over a very long period. Solar, wind, and hydro energy are part of renewable energy [7]. Solar energy comes from the sun and is very abundant in quantity [8]. Indonesia is an equatorial country, so sunlight entering Indonesia is maximal [9]. Electricity generation from solar energy using a specialized device that converts sunlight into electrical energy. This device is commonly referred to as a solar panel.

Based on their movement system, solar panels are divided into static and active [10]. Static solar panels have disadvantages because the solar panels cannot move while the sun moves from east to west [11], hence, sometimes solar panels will not generate efficient energy [12]. To get maximum solar power, solar panels must always face the sun [13]. The sun's position will vary according to its rotation, so the solar panels must be able to follow this movement [14]. The active solar panels are divided into two types of movement, namely single axis and dual axis [15]. A single axis means it only has one actuator that can move the solar panel freely (360°) [16], [17]. In contrast, a dual axis has two actuators that move horizontally and vertically [18], [19].

Besides a solar tracking system, increasing output power efficiency can also be done using reflectors. According to the previous research, mirror reflectors can improve efficiency by 24% [15]. Additionally, mirror reflectors increase efficiency at the minimum possible cost. Adding a reflector in aluminum foil could increase power from 4.87 W to 6.9 W [20]. The data were taken from the average output power from 7 a.m. to 5 p.m. Then, research found that reflective tape can be used as a reflector to reflect sunlight with a reflective coefficient of 70.6% [21]. Based on [22], the reflector angle used for maximum sun reflection is 112.5° with solar panels. Meanwhile, in research [23], solar tracking was created using the fuzzy logic method which could effectively increase the efficiency of solar panels.

Despite these, there is still a need to identify the cost-effectiveness of a combination of tracking systems and reflectors that can maximize solar panel efficiency. This research aimed to fill this gap by integrating dual-axis solar tracking with various reflector materials and optimizing the system using fuzzy logic. The comprehensive comparison of different reflector materials with a tracking system, providing a detailed analysis of efficiency improvements and cost-effectiveness, is the novelty of this research. On the other hand, its potential to offer a practical and cost-effective solution to improve solar panel performance is the significance of this research.

In this research, a comparison of the output efficiency of a dual-axis solar tracking system was carried out by adding three types of reflectors: mirrors, aluminum foil, and reflective tape, then implemented on 50 WP solar panels using the Sugeno fuzzy logic method. The Sugeno approach is chosen for its nonlinear system handling and imperfect input tolerance [24]. It organizes the sophisticated control needed for dual-axis tracking, which must adapt to changing sunlight. Light sensors tell the fuzzy logic controller where to place the solar panels for optimal sun alignment, improving tracking system accuracy and efficiency. Apart from comparing the efficiency of solar panels, a comparison of the price of each reflector used for each increase in the efficiency of the solar panels was also carried out.

II. METHODOLOGY

Efficiency is the parameter most often used to compare the performance of solar panels. One of the quantities that is a parameter for solar panel efficiency is the fill factor [10]. The fill factor calculation will show the ratio of the maximum power obtained from the solar panel to the product of V_{oc} and I_{sc}, based on (1) [25].

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}}. \tag{1}$$

FF indicates fill factor, V_{mp} indicates voltage at maximum power (V), I_{mp} indicates current at maximum power (A), V_{oc} indicates maximum voltage of solar panels under open-circuit conditions (V), and I_{sc} indicates maximum current of solar panels during short circuit (A). The closer to 1 the value of the solar panel fill factor, the higher the efficiency of the solar panel. Based on (1), the size of the fill factor depends on the V_{oc} and I_{sc} values.

Efficiency is the ratio of the energy output from solar panels and the input energy from the sun. The efficiency of solar panels depends on several factors, including the spectrum and intensity of sunlight, the angle of incidence, temperature, shading, and the quality of the solar panel materials. Therefore, one device and another must be carefully used for better efficiency. Solar panel efficiency can be defined as (2).

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{SI \times A}. \tag{2}$$

V_{oc} denotes solar panel open circuit voltage (V), I_{sc} denotes solar panel short circuit current (A), FF denotes fill factor, SI denotes solar irradiation (W/m^2), and A denotes solar panel surface area (m^2).

A. SYSTEM DESIGN

The system comprises a solar panel, four light sensors, two linear actuators, and a reflector. Each sensor will be positioned in four different positions: east, west, north, and south. According to Figure 1, the first linear actuator moves the solar panel horizontally by comparing the light intensity in the east and west. The second linear actuator will move the solar panels vertically by comparing the light intensity in the north and south. The reflector was installed with a width parameter of 40.6 cm and a length adjusted to the size of the solar panel, namely 625 mm.

B. TRACKING SYSTEM TESTING

To validate the tracking process, an electrical circuit assembled and combined on the central pole of the solar panel was needed. The electrical components were 4 BH1750 sensors, which were positioned as in Figure 2, then connected to the PCA7948A multiplexer, and the multiplexer was connected to the Arduino Uno. The power source was a 12 V/10 A power supply, and the motor driver was BTS7960. The electronic circuit of the tracking system can be seen in Figure 3. Proving tracking was done by positioning the light source in four different positions, as shown in Figure 2. Then, the lux value

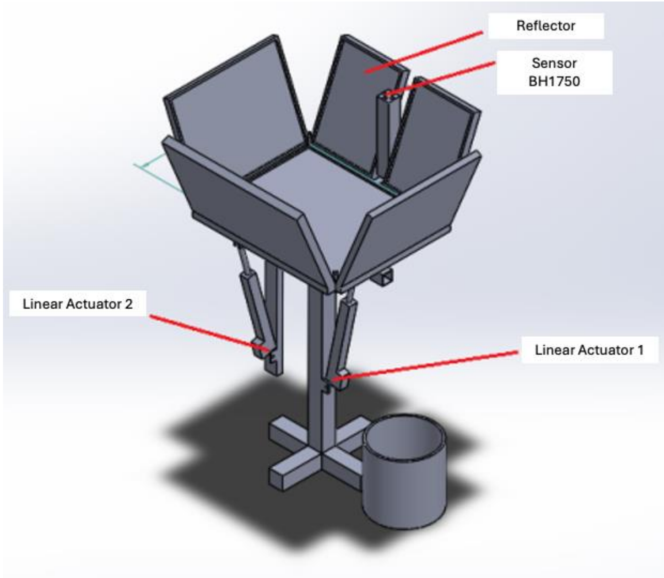

Figure 1. Isometric view of system design.

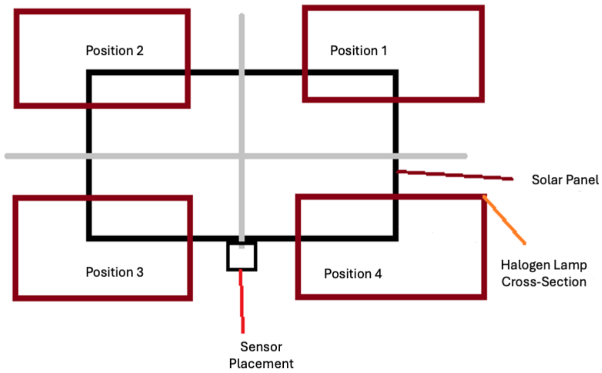

Figure 2. Light source positions.

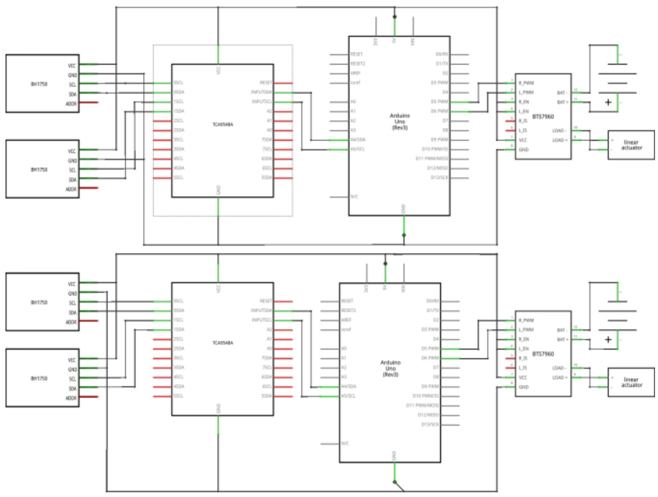

Figure 3. Overall schematic.

data from the BH1750 sensor was taken as initial evidence before the tracking process. Subsequently, tracking was carried out. After running, tracking would stop when the values of the four BH1750 sensors were above 400 and the two motors no longer moved, indicating that the solar panel and the four sensors were pointing at the light source.

C. DATA MEASUREMENT

The V_{oc} and I_{sc} data collection was conducted using a digital multimeter by placing a halogen lamp above the solar panel. There are four data collection schemes: (a) solar panels

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without reflectors, (b) solar panel + mirror reflector, (c) solar panel + aluminum foil reflector, and (d) solar panel + reflective tape reflector.

Retrieving V_{oc} and I_{sc} data helps measure the increase in solar panel efficiency before and after adding reflectors and knowing which reflector is the best in terms of added efficiency value and price. Retrieving V_{oc} and I_{sc} data was done using a digital multimeter by attaching the red (+) cable of the multimeter to the red cable of the solar panel output and the black cable (-) of the multimeter. The first condition tested was a solar panel without a reflector by positioning the halogen lamp perpendicular to the solar panel without a reflector.

III. RESULTS AND DISCUSSION

A. SOLAR TRACKING RESULTS

Lux data were needed before monitoring each position (Figure 2). They were also needed after the tracking to prove that tracking was running, and the solar panel was correctly positioned perpendicular to the light source. At position 1, the initial lux reading showed that the north and east sensors were more significant, indicating that the light position was at the top right (Figure 2). The sensor reading above 400 suggested that the axis had positioned the solar panel perpendicular to the light source. It was based on the calibration of the light sensors used in the system. At the calibration, it was determined that a lux reading of 400 or higher corresponded to the maximum possible light intensity the sensors could detect, which occurred when the solar panel faced the light source perpendicular to the solar panel's surface.

For instance, sensor 1 and 3 readings commenced above 400 after 10 s on sensor 1, while sensor 3 started above 400 after 12 s, indicating that the vertical axis remained at 12 s. On the horizontal axis, sensor 2 reading, as do the two other sensors, is above 400 at 12 s. 4. Therefore, it can be concluded that the tracking process was successful from the initial position parallel to the ground to position 1, taking 12 s. The lux reading value on the horizontal axis had the highest value of 413.83 lx and the lowest value of 100.83 lx. The lowest and highest values were in the input range of the fuzzy logic method, where the input was divided into three categories: dark, normal, and light. Then, the rule table that had been created was applied, and the output was obtained in the form of linear actuator movement clockwise, counterclockwise, or stationary. For example, from second 9 to second 10, the linear actuator moved clockwise because the west sensor reading value was categorized as dark in the fuzzy logic input, and the east sensor reading value was categorized as light. Table I presents data from the initial lux value before running the tracking system until the tracking is successful.

At position 2, the initial lux reading showed that the north and west sensors were more significant, indicating that the light's position was at the top left (Figure 2). When the sensor reading was above 400, it suggested that the axis had positioned the solar panel perpendicular to the light source. For example, sensor 1 and 3 readings on the vertical axis started above 400 after 14 s. Meanwhile, sensor 2 readings were above 400 on the horizontal axis after 13 s, and sensor 4 after 14 s. So, it can be concluded that the tracking process was successful from a parallel starting position. Meanwhile, it required 14 s from position parallel to the ground to point 2. The lux value reading on the horizontal axis had the highest value of 424.17 lx and the lowest value of 96.67 lx. The lowest and highest values

TABLE I
LUX DATA OF POSITION 1

Time (s)	Sensor 1 (North) (lx)	Sensor 2 (West) (lx)	Sensor 3 (South) (lx)	Sensor 4 (East) (lx)
1	157.50	100.83	23.33	158.33
2	210.00	105.00	31.67	157.50
3	212.50	112.50	47.50	177.50
4	279.33	134.17	70.00	198.33
5	286.67	143.33	118.33	198.33
6	359.17	153.33	211.67	203.33
7	370.00	149.17	241.33	199.50
8	370.83	143.33	290.17	28.70
9	372.50	186.67	318.33	319.17
10	415.00	312.50	368.33	342.50
11	419.17	371.67	398.33	395.83
12	421.67	401.67	408.33	410.83
13	418.33	403.33	414.00	406.67
14	415.00	407.00	408.50	409.50
15	418.50	413.83	417.33	407.17
16	413.50	412.17	410.33	411.00
17	421.33	409.00	411.17	407.33
18	412.83	405.50	411.33	413.83
19	412.17	413.0	417.50	405.00
20	41.100	410.50	4120	408.33

were in the input range of the fuzzy logic method, where the input was divided into three categories: dark, normal, and light. Then, the rule table that had been created was applied, and the output was obtained in the form of linear actuator movement clockwise, counterclockwise, or stationary. For example, from second 7 to second 8, the linear actuator movement was reversed (counterclockwise) because the west sensor reading value was categorized as normal in the fuzzy logic input, and the east sensor reading value was categorized as dark. Table II displays data from the initial lux value before running the tracking system until the tracking was successful.

At position 3, the initial lux reading showed that the south sensor and west sensor were more significant, which indicates that the light position is at the bottom left (Figure 2). The sensor reading above 400 suggests the axis positioned the solar panel perpendicular to the light source. For example, sensor 1 and 3 readings on the vertical axis start above 400 after 12 s. Meanwhile, on the horizontal axis, sensor 2 readings started above 400 after 10 s, and sensor 4 readings were above 400 at 12 s. Hence, it can be concluded that the tracking time from position started parallel to the ground until position 3 was 12 s. The lux value reading on the horizontal axis had the highest value of 422.17 lx and the lowest value of 52.5 lx. These lowest and highest values were the input range of the fuzzy logic method, where the input was divided into three categories: dark, normal, and light. For example, from seconds 8 to 9, the linear actuator moves clockwise because the west sensor reading value was categorized as bright in the fuzzy logic input, and the east sensor reading value was categorized as normal. Table III presents data from the initial lux value before running the tracking system until the tracking is successful.

At position 4, the initial lux reading showed that the east and south sensors were significant, indicating that the light was at the bottom right (Figure 2). When the sensor reading was above 400, it suggested that tracking had succeeded in

TABLE II
LUX DATA OF POSITION 2

Time (s)	Sensor 1 (North) (lx)	Sensor 2 (West) (lx)	Sensor 3 (South) (lx)	Sensor 4 (East) (lx)
1	100.83	158.33	25.83	96.67
2	154.17	172.50	51.67	116.67
3	158.33	172.50	84.17	116.67
4	205.83	184.17	93.33	145.83
5	209.17	185.83	109.17	170.83
6	302.50	206.67	133.33	170.00
7	317.50	224.17	150.83	183.33
8	317.50	263.33	161.67	210.83
9	319.17	305.00	190.67	263.33
10	329.17	383.83	233.33	294.17
11	353.33	391.67	312.50	342.50
12	356.67	399.17	365.00	371.67
13	389.33	410.83	385.83	385.83
14	425.00	413.67	414.17	401.17
15	424.17	419.17	410.83	411.67
16	425.33	411.67	421.67	413.33
17	419.17	424.17	422.50	420.00
18	420.17	420.50	418.50	416.83
19	420.33	424.17	417.50	420.33
20	423.00	420.00	422.83	423.33

TABLE III
LUX DATA OF POSITION 3

Time (s)	Sensor 1 (North) (lx)	Sensor 2 (West) (lx)	Sensor 3 (South) (lx)	Sensor 4 (East) (lx)
1	56.67	104.17	76.67	52.50
2	91.67	111.67	130.83	79.17
3	111.67	129.17	179.17	105.00
4	130.00	183.33	185.83	135.83
5	135.83	185.83	285.83	178.33
6	175.83	203.33	288.33	177.50
7	193.33	210.83	295.00	204.17
8	250.83	286.50	312.50	212.50
9	310.00	348.67	315.83	337.50
10	313.33	413.33	336.67	359.17
11	370.00	408.33	363.33	372.50
12	412.50	412.50	414.17	407.50
13	412.67	407.50	414.67	407.50
14	413.50	425.83	418.50	407.33
15	417.33	422.67	414.67	410.83
16	420.83	419.83	416.33	418.83
17	418.00	416.00	417.17	416.00
18	418.33	421.33	418.00	413.17
19	420.00	418.50	421.33	418.67
20	415.83	422.17	421.00	418.50

positioning the solar panel perpendicular to the light source. For example, on the vertical axis, sensor 1 readings started above 400 after 16 s, and sensor 3 readings started above 400 after 14 s. Meanwhile, on the horizontal axis, sensor 2 readings started above 400 after 16 s, and sensor 4 readings started above 400 after 14 s. It was concluded that the tracking system from the initial position parallel to the ground to position 4 took 16 s. The lux value reading on the horizontal axis had the highest value of 425.83 lx and the lowest value of 65 lx. The lowest

TABLE IV
LUX DATA OF POSITION 4

Time (s)	Sensor 1 (North) (lx)	Sensor 2 (West) (lx)	Sensor 3 (South) (lx)	Sensor 4 (East) (lx)
1	62.50	65.00	78.33	74.17
2	115.83	70.33	121.67	68.17
3	136.67	156.67	159.17	158.33
4	140.83	171.17	194.17	183.33
5	157.50	178.33	196.67	185.00
6	175.00	199.83	208.17	202.50
7	200.83	217.50	219.17	265.83
8	205.00	233.33	241.67	265.00
9	210.00	289.00	291.67	300.00
10	275.50	301.67	318.33	314.17
11	303.33	303.33	350.00	341.67
12	310.83	313.33	366.67	385.83
13	318.33	360.83	391.67	397.50
14	372.50	399.17	413.33	405.83
15	396.67	395.00	424.17	400.00
16	412.50	417.50	425.67	423.33
17	413.50	414.17	421.50	424.83
18	414.67	416.67	422.00	425.83
19	418.33	419.83	420.33	420.50
20	420.82	418.00	419.50	421.17

TABLE V
MEASUREMENT DATA

Condition	Voltage (V_{oc}) (V)	Current (I_{sc}) (A)	Efficiency (%)
Normal condition (without treatment)	21.50	0.600	3.40
Solar panel + mirror reflector	24.80	1.150	7.52
Solar panel + aluminum foil reflector	22.22	1.180	6.91
Solar panel + reflective tape reflector	21.80	0.989	5.68

TABLE VI
REFLECTOR PRICE

Type	Price (IDR)
Mirror	82,500
Aluminum foil	18,750
Reflective tape	110,000

and highest values were in the input range of the fuzzy logic method, where the input was divided into three categories: dark, normal, and light. For example, from seconds 11 to 12, the linear actuator movement was clockwise because the west sensor reading value was categorized as normal in the fuzzy logic input, and the east sensor reading value was categorized as bright. Table IV displays data from the initial lux value before running the tracking system until the tracking is successful.

B. SOLAR PANEL EFFICIENCY WITH REFLECTOR IMPLEMENTATION

After it was proven that the tracking process was running, the process tested the solar panel's output efficiency value with and without a reflector. V_{oc} and I_{sc} data are needed to get the solar panel efficiency value, so a digital multimeter is needed.

Table V shows V_{oc} and I_{sc} data for solar panels without reflectors and V_{oc}, I_{sc} data for solar panels with reflectors.

After getting the V_{oc} and I_{sc} values from solar panels with a tracking system implemented for each reflector and solar panels with a tracking system without a reflector implemented, the efficiency value of each treatment was calculated. Equation (2) was used to calculate solar panel efficiency. The fill factor value from (1) was also used. The result of the efficiency calculation of each condition is shown in Table V.

Based on the efficiency calculations, using a mirror reflector could increase the efficiency of solar panels by 4.12%. Aluminum foil reflectors could improve the efficiency of solar panels by 3.51%, and reflective tape reflectors could increase the efficiency of solar panels by 2.29%.

C. CALCULATION OF EFFICIENCY IMPROVEMENT PRICE

Reflector price data are needed to compare reflector prices per increase in solar panel efficiency. Table VI details the reflector price for the experiment kit.

Based on the calculation, the price per increase in efficiency of the solar panel tracking system with the addition of a mirror reflector was IDR20,204 per 1%. Then, with the addition of an aluminum foil reflector, the price was IDR5,341 per 1%. At the same time, the price with the addition of a reflective tape reflector was IDR48,034 per 1%. Focusing solely on the efficiency increase of the solar panel tracking system with the addition of reflectors, mirror reflectors had the highest efficiency increase, achieving 4.12%. However, aluminum foil stands out as the most cost-effective reflector due to its balance of efficiency improvement and lower price.

IV. CONCLUSION

From the research results, it can be concluded that the solar panel tracking system can direct the solar panel toward the light source at all positions. The time required for the tracking system at the light source at position 1 was 12 s, position 2 was 14 s, position 3 was 12 s, and position 4 was 16 s. The efficiency of the solar panel tracking system without a reflector was 3.4%. In contrast, with the addition of a reflector made from mirrors, the efficiency of the solar panel became 7.52%. With the addition of an aluminum foil reflector, the efficiency of the solar panel became 6.92%, and the addition of reflective tape reflectors increased the efficiency of solar panels to 5.6%. Aluminum foil reflectors had the lowest price per increase in efficiency, namely IDR5,341 per 1 %, mirror reflectors were IDR20,204 per 1%, and reflective tape reflectors were IDR48,034 per 1%.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

AUTHORS' CONTRIBUTIONS

Conceptualization, Alvin Rinaldi Wiharja and Levin Halim; methodology, Alvin Rinaldi Wiharja and Faisal Wahab; software, Alvin Rinaldi Wiharja; validation, Alvin Rinaldi Wiharja, Levin Halim, Faisal Wahab; formal analysis, Alvin Rinaldi Wiharja; investigation, Alvin Rinaldi Wiharja; resources, Alvin Rinaldi Wiharja; data curation, Alvin Rinaldi Wiharja and Faisal Wahab; writing—original draft preparation, Alvin R. Wiharja and Levin Halim; writing—reviewing and editing, Levin Halim; visualization, Alvin Rinaldi Wiharja and Levin Halim; supervision, Levin Halim and Faisal Wahab; project administration, Levin Halim.

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