

## Article

# The Impact of Large-Scale Social Restriction Phases on the Air Quality Index in Jakarta

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**Abstract:** We reported the result of our study on the impact of Large-Scale Social Restriction (LSSR) phases due to the COVID-19 outbreak on the air quality in Jakarta. Specifically, this study covered the change of Air Quality Index (AQI) based on five pollutants, PM<sub>10</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, and NO<sub>2</sub>, contained in Jakarta's air before and during LSSR. The AQI data were provided by the Ministry of Environment and Forestry, Indonesia, from January 2019 to December 2020 at five different locations in Jakarta, with missing data for March and September 2020 due to unknown reasons. These data were grouped into the period before the LSSR from January 2019 to February 2020 and the period during LSSR from April 2020 to December 2020. In order to measure the change in the air quality of Jakarta before and during LSSR, we ran a chi-squared test to the AQI for each location and LSSR phase as well as paired one-sided *t*-test for the seasonal trend. The result of this study showed that, in general, LSSR improved the air quality of Jakarta. The improvement was mainly contributed by reduced transportation activities that were induced by LSSR. Further analysis on the seasonal pollutants trend showed a variation of AQI improvement in each phase due to their unique characteristics.

**Keywords:** air quality; Jakarta; lockdown; large-scale social restriction; COVID-19

## 1. Introduction

Since the first case was confirmed in November 2019 in Wuhan, China [1], COVID-19 has quickly spread worldwide, which was declared as a global pandemic on 11 March 2020 by the World Health Organization (WHO) [2]. The quick spread of COVID-19 is caused by its highly contagious characteristic in terms of human-to-human transmission. Therefore, the most effective approach to suppress the growth of the spread is to administer a form of social restriction. However, because it tends to reduce economic activities, the local government needs to consider the regional economic condition in determining a suitable level of social restriction without harming the economy of the region.

In Indonesia, the government issued a policy called Large-Scale Social Restriction (LSSR), which is a more tolerant version of lockdown, as a countermeasure to control the COVID-19 spread. The LSSR policy was put into action beginning on 10 April 2020 to control the spread of COVID-19 while preventing any potential economic crisis that might emerge due to excessive social restriction. The typical strict lockdown is not suitable to be implemented in Indonesia because even with LSSR, Indonesia still suffered substantial impairment to the national economy [3].

LSSR was a flexible policy that allowed the Indonesian government to adjust the level of anthropogenic activity restriction according to the current economic situation and spread of COVID-19 in a certain region. In Jakarta, LSSR has been implemented in four phases with different levels of restriction. The first phase was implemented under the DKI Jakarta Governor Regulation No. 33/2020 [4] from 10 April 2020 to 23 April 2020. This phase was similar to the typical lockdown in other countries, which was characterized by a total shutdown of operations in all sectors except the vital sectors such as basic needs logistics, public services, and communication. The second phase was dubbed the transition phase by the Jakarta government, delivering a message that the lockdown-like restriction in the previous phase was replaced with a more relaxed restriction as long as the spread of COVID-19 was manageable. This phase was implemented under the DKI Jakarta Governor Regulation No. 51/2020 [5] from 4 June 2020 to 13 September 2020. The key characteristic of this phase was the relaxation of the social activities prohibition of the previously restricted sectors. For instance, an office of the previously restricted sectors can be occupied by 50% of workers. The restricted occupation rate also applied to other types of public enclosed spaces such as factories and schools. In order to prevent any potential COVID-19 transmission caused by the relaxation, the government conducted a massive public education of health protocol during this phase. This phase aimed to observe if further relaxation can be implemented, for example, increasing the percentage of office room occupation by 75%. However, because of the increase in COVID-19 spread during this phase, the government applied more restrictions starting from 14 September 2020. This was officially dubbed the second regular LSSR phase by the government, which was implemented under the DKI Jakarta Governor Regulation No. 88/2020 [6]. The restriction was not as strict as the first regular LSSR phase, in which 25% of office room occupation was allowed. This phase ended on 11 October 2020 and was replaced by the second transition with the same characteristics as the first transition phase. This phase was effectively applied until December 2020 under the DKI Jakarta Governor Regulation No. 101/2020 [7]. In Table 1, we summarized the LSSR phases that have been implemented from April 2020 to December 2020 in Jakarta.

**Table 1.** LSSR Phases in Jakarta from April 2020 to December 2020.

Name of the Phase	Period	Key Characteristics
The 1st regular LSSR phase	10 April–3 June	Total shutdown of social interaction in non-vital sectors
The 1st transition phase	4 June–13 September	Fifty percent of office room occupation was allowed for the previously restricted sectors
The 2nd regular LSSR phase	14 September–11 October	Twenty-five percent of office room occupation was allowed for the previously restricted sectors
The 2nd transition phase	12 October–21 December	Fifty percent of office room occupation was allowed for the previously restricted sectors

As a metropolitan city, the sources of air pollution in Jakarta are mostly from transportation sectors [8]. Thus, the anthropogenic activity changes induced by LSSR should

improve the air pollution in Jakarta. This hypothesis is supported with global evidences of the improvement of air quality with the implementation of anthropogenic activity restrictions due to the COVID-19 outbreak. The improvement was first confirmed via satellite observation [9–12]. Other studies also observed the air quality improvement from pollutant concentration data in specific regions such as East Asia [13–16], South Asia [17–19], Southeast Asia [20–23], Europe [24–33], North America [34,35], and South America [36–38]. The studied pollutants vary between studies but include at least one of the particulate matter (PM) pollutants and/or the gaseous pollutants (e.g., SO<sub>2</sub>, CO, O<sub>3</sub>, and NO<sub>x</sub>).

Specifically in Jakarta, the effect of LSSR on air quality has been studied by Anugerah et al. [22]. The air quality they studied was based on the concentration data of five pollutants: PM<sub>10</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, and NO<sub>2</sub>. The data were obtained from five locations in Jakarta, each representing the cities in Jakarta, i.e., Central, North, South, East, and West Jakarta. The study provided descriptive statistics of the air quality change in Jakarta due to LSSR as well as a statistical test on the air quality change before and during LSSR for five pollutants in five cities in Jakarta. They also presented the descriptive statistics of the air quality in three different periods: pre-LSSR (1 January 2020–9 April 2020), during LSSR (10 April 2020–4 June 2020), and post-LSSR (5 June–30 June). The post-LSSR period defined in the study is actually part of the aforementioned first transition phase of LSSR, which still prohibited unnecessary anthropogenic interactions but with a more lenient restriction. Other than the aforementioned five pollutants, PM<sub>2.5</sub> reduction was also observed during LSSR in Jakarta [23].

Although the social restriction policy of LSSR can improve the air quality in Jakarta, each phase in LSSR might have a different effect on the air quality. This is due to the different levels of restrictions applied in each phase. Therefore, we conducted a detailed investigation on the air quality change in Jakarta for each LSSR phase. Specifically, we tested the overall Air Quality Index (AQI) changes between the period of the LSSR phase in 2020 and its corresponding period in 2018 and 2019 with a chi-squared test as well as the seasonal AQI trend of each pollutant with a *t*-test. The tests were conducted on the data from the same five locations used by Anugerah et al. We also conducted a chi-squared test on the overall AQI change from 2018 and 2019 to 2020 to observe if LSSR in general improved the air quality in Jakarta.

## 2. Materials and Methods

### 2.1. Dataset

The data in this study were obtained from the official Jakarta city council portal ([data.jakarta.go.id](https://data.jakarta.go.id)), which were originally provided by the Ministry of Environment and Forestry, Indonesia. For this study, we acquired the data in the year of 2018, 2019, and 2020. This dataset is illustrated in Figure 1. It comprises eight columns: Date, Location ID, PM<sub>10</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, NO<sub>2</sub>, and AQI Category.

The first two columns indicated the measurement date and location of the data. The data were measured on a daily basis, which means that only one measurement per day was recorded in this dataset for each measurement location. Meanwhile, the measurement locations were spread in five different spots across the city regions in Jakarta as observed in Figure 2. Each location has its own characteristics, which we summarized in Table 2.

Date	Location ID	PM10	SO2	CO	O3	NO2	AQI Category
2018-01-01	DKI1	35.0	20.0	22.0	27.0	2.0	GOOD
2018-01-01	DKI2	59.0	29.0	36.0	33.0	9.0	MODERATE
2018-01-01	DKI3	14.0	17.0	22.0	35.0	5.0	GOOD
2018-01-01	DKI4	76.0	31.0	31.0	33.0	6.0	MODERATE
2018-01-01	DKI5	45.0	19.0	38.0	20.0	4.0	GOOD
...	...	...	...	...	...	...	...
2020-12-31	DKI1	26.0	25.0	8.0	29.0	10.0	GOOD
2020-12-31	DKI2	33.0	16.0	11.0	64.0	9.0	MODERATE
2020-12-31	DKI3	41.0	10.0	9.0	24.0	27.0	GOOD
2020-12-31	DKI4	28.0	36.0	10.0	27.0	3.0	GOOD
2020-12-31	DKI5	18.0	13.0	6.0	24.0	3.0	GOOD

Figure 1. An illustration of the dataset we used in this study.



Figure 2. Air Quality Measurement Locations in Jakarta.

Table 2. Measurement location characteristics.

Code	Location	Region	Characteristic
DKI1	Bundaran HI	Central Jakarta	Office district
DKI2	Kelapa Gading	North Jakarta	Crowded residential close to industrial parks
DKI3	Jagakarsa	South Jakarta	Crowded residential
DKI4	Lubang Buaya	East Jakarta	Less crowded residential and recreation spot
DKI5	Kebon Jeruk	West Jakarta	Crowded residential, offices, and shops

The following five columns (PM<sub>10</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, and NO<sub>2</sub>) were the AQI data that were derived from the real measured ambient of five air pollutants, namely PM<sub>10</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, and NO<sub>2</sub>, with the following equation:

$$AQI = \frac{AQI_u - AQI_l}{X_u - X_l}(X - X_l) + AQI_l \tag{1}$$

where

AQI = Standardized AQI;

AQI<sub>u</sub> = AQI upper limit;

AQI<sub>l</sub> = AQI lower limit;

X = Real measured ambient;

X<sub>u</sub> = Ambient upper limit;

X<sub>l</sub> = Ambient lower limit.

The last column contained a summarizing categorical variable of the previous five columns. It was computed by taking the maximum AQI among the five pollutants in one day. Afterward, it was categorized based on the rule in Table 3.

**Table 3.** Air Quality Categorization.

Category	Value Range
Good	0–50
Moderate	51–100
Unhealthy	101–199
Very Unhealthy	200–299
Hazardous	300 or more

### 2.2. Statistical Analysis

For the statistical analysis, we grouped the 2020 data into five groups based on the following five periods that we named in the following manner: Pre-LSSR (1 January–28 February), REG1 (10 April–3 June), TR1 (4 June–31 August), REG2 (1 October–11 October), and TR2 (12 October–21 December). REG1, TR1, REG2, and TR2 were, respectively, the first regular, first transition, second regular, and second transition LSSR phase in Table 1, omitting September 2020 which was missing in the provided data. The Pre-LSSR phase is the period before LSSR in 2020. The data for the Pre-LSSR period were taken only from January to February due to missing data in March 2020. In order to compare these five groups of 2020 data, we also grouped the 2018 and 2019 data with the same period and ignored the year. Finally, we paired the 2020 groups with their 2019 group counterpart for two-group statistical tests.

The first statistical test we ran was a chi-squared test on the AQI category variable in the last column of the dataset. The test was conducted for all data and the subsets of the data based on the locations and phases. Subsequently, we conducted the second test for the change of AQI for each pollutant by averaging the AQI of a particular pollutant (the third to seventh column) in all measured locations and tested the change between the aforementioned time-period-based pairs of groups with a paired one-sided *t*-test. For all statistical tests, we used a 95% confidence level, which means that the comparison is considered statistically significant if the *p*-value is less than 0.05. All the statistical tests were conducted in Python using SciPy library [39].

Additionally, we also conducted two descriptive statistics analyses. The first analysis was conducted to compare the distribution of AQI between weekdays and weekends. For this analysis, we plotted the count of the AQI category that was grouped by whether the day is weekday or weekend and normalized to the total days in the corresponding year. The second analysis was carried out by plotting the distribution of the AQI of each

pollutant, grouped by phase and year. This analysis was conducted to complement the result of the aforementioned paired one-sided *t*-test.

### 3. Results

In Table 4, we summarized the AQI change between the year 2018–2020 and 2019–2020 in the five measured locations in Jakarta. In general, the air quality in Jakarta in 2020 improved compared to 2018 and 2019. From 2018, the improvement was indicated by the reduction in days with very unhealthy (−25 days) and unhealthy (−200 days) index as well as the increase in days with good (+17 days) and moderate (+208 days) index. The improvement was statistically significant with  $\alpha = 0.05$  ( $p$ -value =  $2.42 \times 10^{-32}$ ). Meanwhile, from 2019, the days with very unhealthy, unhealthy, and moderate decreased by 7, 178, and 5 days, respectively. The days with good index were increased by 190 days. The improvement from 2019 was also significant with  $p$ -value =  $4.57 \times 10^{-36}$ .

**Table 4.** The comparison of AQI from the year of 2018 and 2019 to 2020 based on the measurement location in Jakarta.

Location	Year	Good	Moderate	Unhealthy	Very Unhealthy	<i>p</i> -Value
All	2018	323	828	297	25	$2.42 \times 10^{-32}$ *
	Diff. to 2020	17	208	−200	−25	
	2019	151	1052	271	7	$4.57 \times 10^{-36}$ *
	Diff. to 2020	190	−5	−178	−7	
DKI1	2018	144	144	4	0	$8.66 \times 10^{-3}$ *
	Diff. to 2020	−36	37	−1	0	
	2019	49	232	13	0	$8.73 \times 10^{-8}$ *
	Diff. to 2020	57	−47	−10	0	
DKI2	2018	53	147	88	10	$4.35 \times 10^{-15}$ *
	Diff. to 2020	14	66	−70	−10	
	2019	32	228	41	0	$1.43 \times 10^{-5}$ *
	Diff. to 2020	36	−13	−23	0	
DKI3	2018	45	175	68	0	$3.09 \times 10^{-8}$ *
	Diff. to 2020	4	46	−50	0	
	2019	10	201	84	0	$1.85 \times 10^{-17}$ *
	Diff. to 2020	43	25	−68	0	
DKI4	2018	46	239	8	0	$1.73 \times 10^{-1}$
	Diff. to 2020	13	−18	5	0	
	2019	33	209	46	0	$1.70 \times 10^{-6}$ *
	Diff. to 2020	24	10	−34	0	
DKI5	2018	35	123	129	15	$4.63 \times 10^{-17}$ *
	Diff. to 2020	22	77	−84	−15	
	2019	27	182	87	7	$3.43 \times 10^{-7}$ *
	Diff. to 2020	30	20	−43	−7	

\* Significant at 95% confidence level ( $\alpha = 0.05$ ).

A detailed observation of the AQI changes within each LSSR phase revealed that not all phases have improved AQI from 2019 to 2020. Only the first and second transition phases had significantly improved AQI as suggested in Table 5. However, it is worth noticing that the improvement of the first regular LSSR phase was almost significant with  $p$ -value =  $5.77 \times 10^{-2}$ . Meanwhile, improved AQI was observed in all phases from 2018 to 2020. Interestingly, the AQI of the Pre-LSSR phase in 2020 significantly improved from 2019, while it significantly declined from 2018.

The descriptive analysis on the weekdays and weekends in Figure 3 revealed that the same pattern occurred on the weekdays and weekends within the same year. This



indicated that the difference in the level of anthropogenic activities in Jakarta during weekdays and weekends was negligible and that it did not affect the distribution of the overall AQI categories in the same year. However, the distribution between years was noticeably different. The air quality in 2019 was in general worse than in 2018 with the increase in moderate and unhealthy days. However, the air quality in 2020 was observed to be improved with an increase in days with good and moderate AQI and a decrease in unhealthy AQI days.



**Figure 3.** The descriptive statistics of the overall AQI on weekdays versus weekends in 2018, 2019, and 2020.

**Table 5.** The summary of the AQI change within the LSSR phases for all locations. REG1 is the first regular LSSR phase, TR1 is the first transition LSSR phase, REG2 is the second regular LSSR phase, and TR2 is the second transition LSSR phase. Pre-LSSR is the period between 1 January to 28 February, which is before the LSSR phases in 2020. Notice that we did not include March in the pre-LSSR period because the data were missing for the year 2020.

Phase	Year	Good	Moderate	Unhealthy	Very Unhealthy	p-Value
Pre-LSSR	2018	161	125	1	0	$3.13 \times 10^{-4}$ *
	Diff. to 2020	-32	19	13	0	
	2019	99	171	20	0	$2.18 \times 10^{-2}$ *
	Diff. to 2020	32	-26	-6	0	
REG1	2018	32	188	44	1	$2.80 \times 10^{-3}$ *
	Diff. to 2020	15	11	-25	-1	
	2019	34	206	32	0	$5.77 \times 10^{-2}$
	Diff. to 2020	14	-1	-13	0	
TR1	2018	18	247	149	15	$6.10 \times 10^{-30}$ *
	Diff. to 2020	-1	142	-126	-15	
	2019	5	345	84	2	$1.70 \times 10^{-10}$ *
	Diff. to 2020	12	52	-62	-2	
REG2	2018	8	27	19	0	$5.92 \times 10^{-4}$ *
	Diff. to 2020	-8	17	-9	0	
	2019	1	33	18	1	$1.33 \times 10^{-1}$
	Diff. to 2020	-1	10	-8	-1	
TR2	2018	42	215	79	8	$4.20 \times 10^{-12}$ *
	Diff. to 2020	58	1	-51	-8	
	2019	8	224	105	2	$5.89 \times 10^{-28}$ *
	Diff. to 2020	92	-10	-80	-2	

\* Significant at 95% confidence level ( $\alpha = 0.05$ ).

In Figure 4, we plotted the AQI seasonal trend of PM<sub>10</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, and NO<sub>2</sub> in a box plot for each phase in the year of 2018, 2019, and 2020. The numerical value of the AQI average of each pollutant in each period and the statistical test result of the change from 2019 to 2020 are presented in Tables 6 and 7. A mixed result was observed in the Pre-LSSR phase. The AQI of all pollutants from 2018 to 2020 in this phase declined except for SO<sub>2</sub>, which improved. From 2019 to 2020, the AQI of PM<sub>10</sub> and SO<sub>2</sub> showed no significant change, O<sub>3</sub> and NO<sub>2</sub> showed significant improvement, and CO showed significant decline. In contrast, the AQI of all pollutants in the REG1 and TR1 phases improved in general. Only the AQI of SO<sub>2</sub> from 2019 to 2020 in both phases significantly declined. We also observed no significant change in the AQI of SO<sub>2</sub> and NO<sub>2</sub> in the TR1 phase from 2018 to 2020.

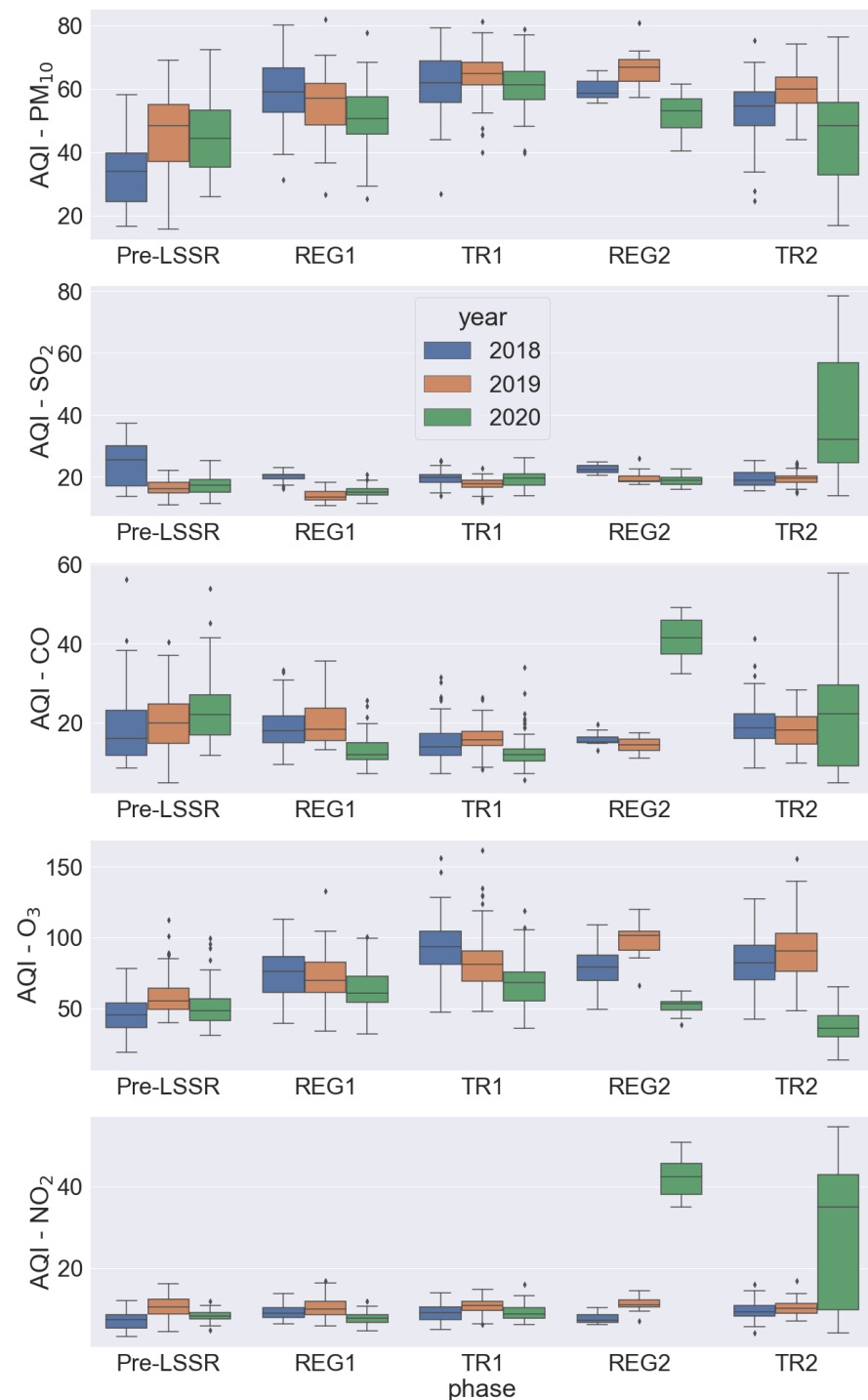
**Table 6.** The change of average AQI from 2018 and 2019 to 2020 of each pollutant within the Pre-LSSR, REG1, and TR1 phase.

Phase	Pollutant	Compared Years	Average		Difference of Average	<i>p</i> -Value
			Year 1	Year 2		
Pre-LSSR	PM <sub>10</sub>	2018–2020	32.56	45.30	−12.74	$5.21 \times 10^{-26} *$
		2019–2020	45.44	45.30	0.15	$4.50 \times 10^{-1}$
	SO <sub>2</sub>	2018–2020	24.68	17.08	7.60	$4.96 \times 10^{-16} *$
		2019–2020	16.43	17.08	−0.65	$1.57 \times 10^{-1}$
	CO	2018–2020	19.14	23.53	−4.39	$1.68 \times 10^{-5} *$
		2019–2020	19.83	23.53	−3.70	$6.72 \times 10^{-6} *$
	O <sub>3</sub>	2018–2020	42.95	51.67	−8.72	$1.65 \times 10^{-7} *$
		2019–2020	58.67	51.67	7.00	$6.24 \times 10^{-4} *$
	NO <sub>2</sub>	2018–2020	6.97	8.21	−1.24	$1.20 \times 10^{-4} *$
		2019–2020	10.46	8.21	2.24	$2.15 \times 10^{-12} *$
REG1	PM <sub>10</sub>	2018–2020	60.08	51.30	8.78	$2.75 \times 10^{-11} *$
		2019–2020	55.73	51.30	4.43	$4.07 \times 10^{-5} *$
	SO <sub>2</sub>	2018–2020	19.63	14.94	4.69	$5.55 \times 10^{-16} *$
		2019–2020	13.93	14.94	−1.01	$1.88 \times 10^{-2} *$
	CO	2018–2020	18.91	13.17	5.75	$1.21 \times 10^{-20} *$
		2019–2020	19.84	13.17	6.67	$9.54 \times 10^{-22} *$
	O <sub>3</sub>	2018–2020	74.24	63.23	11.00	$7.68 \times 10^{-6} *$
		2019–2020	71.34	63.23	8.11	$4.24 \times 10^{-6} *$
	NO <sub>2</sub>	2018–2020	9.25	7.41	1.84	$3.36 \times 10^{-7} *$
		2019–2020	10.45	7.41	3.04	$1.39 \times 10^{-29} *$
TR1	PM <sub>10</sub>	2018–2020	62.16	61.63	0.53	$2.36 \times 10^{-1}$
		2019–2020	64.58	61.63	2.95	$1.26 \times 10^{-6} *$
	SO <sub>2</sub>	2018–2020	19.67	19.30	0.36	$1.86 \times 10^{-1}$
		2019–2020	17.48	19.30	−1.82	$3.38 \times 10^{-7} *$
	CO	2018–2020	15.03	12.74	2.29	$6.69 \times 10^{-8} *$
		2019–2020	15.90	12.74	3.16	$5.26 \times 10^{-14} *$
	O <sub>3</sub>	2018–2020	94.01	67.44	26.57	$2.37 \times 10^{-28} *$
		2019–2020	82.84	67.44	15.40	$2.87 \times 10^{-22} *$
	NO <sub>2</sub>	2018–2020	9.09	9.19	−0.10	$3.77 \times 10^{-1}$
		2019–2020	10.62	9.19	1.43	$3.34 \times 10^{-10} *$

\* Significant at 95% confidence level ( $\alpha = 0.05$ ).



A different pattern was observed in the REG2 and TR2 phases. In both phases, the AQI of PM<sub>10</sub> and O<sub>3</sub> significantly improved from both 2018 and 2019 to 2020. On the other hand, the AQI of CO and NO<sub>2</sub> significantly declined in both phases from both 2018 and 2019 to 2020. Meanwhile, the AQI change of SO<sub>2</sub> in the TR2 phase significantly declined from both 2018 and 2019 to 2020. A mixed AQI change pattern of SO<sub>2</sub> was found in the REG2 phase, which was different from the TR2 phase. Significant improvement was found from 2018 to 2020 while no significant change was observed from 2019 to 2020.



**Figure 4.** The AQI seasonal trend of PM<sub>10</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, and NO<sub>2</sub> in Jakarta in 2018, 2019, and 2020 grouped by the phases described in Section 2.2. The AQI was averaged over the five measured locations in Jakarta.

**Table 7.** The change of average AQI from 2018 and 2019 to 2020 of each pollutant within the REG2 and TR1 phase.

Phase	Pollutant	Compared Years	Average		Difference of Average	p-Value
			Year 1	Year 2		
REG2	PM <sub>10</sub>	2018–2020	59.98	52.22	7.76	$1.41 \times 10^{-3*}$
		2019–2020	67.65	52.22	15.43	$4.35 \times 10^{-12*}$
	SO <sub>2</sub>	2018–2020	22.65	18.89	3.76	$2.14 \times 10^{-2*}$
		2019–2020	19.89	18.89	1.00	$3.37 \times 10^{-1}$
	CO	2018–2020	15.78	41.44	−25.66	$1.10 \times 10^{-5*}$
		2019–2020	13.86	41.44	−27.58	$9.39 \times 10^{-6*}$
	O <sub>3</sub>	2018–2020	79.31	51.85	27.46	$1.02 \times 10^{-3*}$
		2019–2020	98.75	51.85	46.90	$4.29 \times 10^{-7*}$
	NO <sub>2</sub>	2018–2020	7.79	42.04	−34.25	$5.08 \times 10^{-8*}$
		2019–2020	11.26	42.04	−30.77	$1.38 \times 10^{-6*}$
TR2	PM <sub>10</sub>	2018–2020	53.03	45.31	7.72	$5.81 \times 10^{-15*}$
		2019–2020	59.90	45.31	14.58	$1.14 \times 10^{-48*}$
	SO <sub>2</sub>	2018–2020	19.54	40.28	−20.74	$3.89 \times 10^{-43*}$
		2019–2020	19.52	40.28	−20.76	$5.21 \times 10^{-36*}$
	CO	2018–2020	19.48	23.04	−3.55	$4.64 \times 10^{-3*}$
		2019–2020	17.84	23.04	−5.20	$1.28 \times 10^{-4*}$
	O <sub>3</sub>	2018–2020	84.50	36.85	47.65	$2.18 \times 10^{-54*}$
		2019–2020	92.47	36.85	55.62	$3.34 \times 10^{-82*}$
	NO <sub>2</sub>	2018–2020	9.50	30.35	−20.85	$2.34 \times 10^{-28*}$
		2019–2020	10.20	30.35	−20.15	$2.15 \times 10^{-28*}$

\* Significant at 95% confidence level ( $\alpha = 0.05$ ).

#### 4. Discussion

The effect of LSSR in improving the air quality in Jakarta was evident from the statistical test between the years 2018 and 2020. In particular, the AQI change significantly declined in the Pre-LSSR phase and significantly improved in all the LSSR phases (REG1, TR1, REG2, and TR2). However, the fact was not too apparent from the statistical test between the years 2019 and 2020.

At first, the insignificant change of the overall AQI in the REG1 phase from 2019 to 2020 seemed counterintuitive in comparison to the statistical test result between the years 2018 and 2020. However, by investigating the details of the AQI change of each pollutant, we found that the AQI of the pollutants that were mainly generated from the transportation sector was indeed improved. According to Jakarta's emission inventory reported by Lestari et al. [8], the majority of  $NO_x$ , CO, and particulate matters in Jakarta were generated by the transportation sector. The statistical test result in Table 6 shows that  $NO_2$ , CO, and  $PM_{10}$  were significantly improved in the REG1 phase. Thus, we can infer that the social restriction in this phase indeed improved Jakarta's air quality by reducing transportation activities. The reason why the overall change was not significant can be attributed to the significant increase in the  $SO_2$  AQI, which was mainly generated by industrial activities in Jakarta [8]. This suggested that, although the activities in the transportation sector were reduced in this phase, the industrial activities were increased instead.

In contrast to the previous phase, the overall AQI in the TR1 phase improved significantly from 2019 to 2020. In detail, the AQI of all pollutants except  $SO_2$  significantly improved. This pattern is similar to the pattern in the previous phase, meaning that the transportation activities decreased and otherwise increased for industrial activities. However, because the overall AQI improvement was significant, it can be concluded that the

AQI improvement from the transportation sector contributed more to the overall AQI than the declined air quality from the industrial sector.

A different pattern emerged in the REG2 phase from 2019 to 2020. Similar to its REG1 counterpart, the overall change of AQI in the REG2 phase was not significant. However, the details were different. In this phase, the pollutants with significant AQI improvement were  $PM_{10}$  and  $O_3$ . The AQI of  $SO_2$  also improved although it was not significant. Meanwhile, the CO and  $NO_2$  AQI significantly declined. The decline of the CO and  $NO_2$  AQI suggested that the transportation activities in this phase increased because the main source of both pollutants is the transportation sector. Although the majority of  $PM_{10}$  sources were also from transportation, it was also generated by industrial activities by a large portion [8]. Given that  $SO_2$  also improved, although it was not significant, it can be concluded that the industrial activities in this phase decreased. Thus, the declined AQI from the transportation sector was canceled by the AQI improvement from the industrial sector, resulting in the insignificant overall AQI change in this phase.

Meanwhile, the overall AQI of the TR2 phase from 2019 to 2020 was significantly improved with  $PM_{10}$  and  $O_3$  as the main contributors. The other three pollutants ( $SO_2$ , CO, and  $NO_2$ ), however, were significantly declined, although the effect was overshadowed by the  $PM_{10}$  and  $O_3$  AQI improvement. With the mixed type of sources that generated  $PM_{10}$  in Jakarta, it can be inferred that the activities of both transportation and industrial sectors tended to decrease in this phase.

Among all the pollutants, only  $PM_{10}$  and  $O_3$  AQI were relatively consistent to be improved due to the LSSR phases. The improvement was specifically apparent in REG2 and TR2 phases. In detail, CO was improved in all LSSR phases both from 2018 and 2019 to 2020. Meanwhile, the change of  $PM_{10}$  AQI was not significant only from 2018 to 2020 in TR1 among all the LSSR phases. On the other hand, the AQI of  $SO_2$ , CO, and  $NO_2$  declined in some of the LSSR phases. Both CO and  $NO_2$  significantly declined in REG2 and TR2, while they significantly improved in REG1 and TR1, except for the AQI change of  $NO_2$  in TR1 from 2018 to 2020. Meanwhile, the change of  $SO_2$  AQI was mixed in the LSSR phases. It was improved in REG1 2018–2020 and REG2 2018–2020, not significantly changed in TR1 2018 and REG2 2019, and declined in REG1 2019–2020, TR1 2019–2020, TR2 2018–2020, and TR2 2019–2020.

Interestingly, we observed a significant improvement of the overall AQI in the Pre-LSSR from 2019 to 2020. This suggested that, even without LSSR, the air quality in Jakarta might improve in 2020 from 2019. The main contributors to the improvement were  $O_3$  and  $NO_2$ . Since  $O_3$  is a by-product of  $NO_2$ , it is valid to assume that the sole main contributor was  $NO_2$ . The other pollutant with significant AQI change in this period was CO with a declining trend. Based on the emission inventory reported by Lestari et al. [8], both  $NO_x$  and CO were mostly generated by transportation activities. However, the majority of  $NO_x$  was from heavy-duty vehicles while CO was mostly from light-duty vehicles. Thus, we concluded that the cargo activities were diminished in this period, which was the main contributor to the overall AQI improvement.

Similar to our study, Anugerah et al. [22] also performed analysis of the seasonal trend of the AQI of the same four primary pollutants in our study ( $PM_{10}$ ,  $SO_2$ , CO, and  $NO_2$ ), although the period was limited only from 1 January to 30 June. A similar trend that we observed in our study emerged from their study. They reported an improvement of  $PM_{10}$  caused by LSSR up to 3.3% in April, 15.4% in May, and 2.4% in June according to their year-on-year comparison of 2020 to 2019 and 2018. The AQI of the other primary pollutants ( $SO_2$ , CO, and  $NO_2$ ) improved from 7.5% to 39.9%. Their definition of LSSR is the same as the first regular LSSR period that we defined in this paper. In the first regular LSSR period, we also observed a statistically significant improvement of three primary pollutants ( $PM_{10}$ , CO, and  $NO_2$ ). However, we found that  $SO_2$  was statistically declined, which seems contradictory to the Anugerah et al. report. Upon a closer investigation into their seasonal trend plot, we observed that the AQI of  $SO_2$  in this period declined in general. The improvement of  $SO_2$  was observed only in several weeks during this period.

In comparison to the other major cities in Southeast Asia, the air quality in Jakarta can be improved further if more restrictive policies, such as suspended international flights, restricted vehicular movements, and banned business operations that gathered a large number of people, were implemented. As reported by Roy et al. [40], the concentration of several pollutants was improved by a large margin at Kuala Lumpur and Singapore, which established a heavily restrictive policy to limit the spread of the novel coronavirus named ‘Movement Control Order’ and ‘Circuit Breaker’. In Singapore, a significant drop of NO<sub>2</sub> and SO<sub>2</sub> concentration was observed (48.71% and 16.32%, respectively). In Kuala Lumpur, a significant drop was indicated when SO<sub>2</sub> dropped 21.92% from the previous average concentration. On the contrary, Roy et al. reported that Jakarta experienced a rising amount of SO<sub>2</sub> up to 5.88%.

## 5. Conclusions

In general, we found that the air quality improved in Jakarta due to LSSR, which was evidenced by the statistical test result of the overall AQI and the AQI of each pollutant in this study (PM<sub>10</sub>, SO<sub>2</sub>, CO, and NO<sub>2</sub>). The statistical test between the year 2019 and 2020 of the overall AQI revealed an interesting fact that the significant AQI improvement happened only in the transition phase of LSSR but not in the regular phase, which has more restriction. Although this sounds counterintuitive, it does not mean that the induced social mobility change during the regular LSSR did not affect the AQI change. Based on the seasonal trend analysis of each pollutant, we observed a general improvement of the AQI from the transportation sector emission in all LSSR phases. Therefore, we can conclude that LSSR improved Jakarta’s air quality because the policy was more restrictive towards social activity that generated traffic but more lenient toward the industry in order to prevent economic collapse. In the future, in order to maintain improved air quality, the government should consider encouraging remote working, which was forced to be implemented during LSSR to prevent the spread of COVID-19 in Indonesia. Even without the COVID-19 pandemic, several jobs can be performed remotely without compromising productivity. By maintaining remote working for these types of jobs, Jakarta can maintain improved air quality to some extent.

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## Abbreviations

The following abbreviations are used in this manuscript:

AQI    Air Quality Index;  
LSSR    Large-Scale Social Restriction.

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