

Original article

# Comparative Analysis of Oxygen Availability and Demand in Klojen and Kedungkandang Districts, Malang City, Using NDVI-Based Vegetation Assessment

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## Abstract

Urban areas face increasing ecological pressures due to growing population density, transportation, and land use conversion, which trigger environmental imbalances. This study aims to analyze the balance between oxygen availability and oxygen demand in Kedungkandang and Klojen Districts, Malang City, using the Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 imagery as the basis for estimating oxygen supply. The analysis covers the period from 2019 to 2024 and employs a quantitative spatial approach. Oxygen demand was calculated based on oxygen consumption from humans, motor vehicles, and livestock, while oxygen availability was estimated by converting NDVI values into biomass, carbon stock, and annual oxygen production from vegetation. This approach provides a comprehensive overview of the vegetative ecosystem's capacity to support oxygen balance within urban environments. The results indicate that Kedungkandang District has higher oxygen availability compared to Klojen District due to its wider and more continuous vegetation cover. In contrast, Klojen District experiences an increasing oxygen deficit each year, driven by population growth and the dominance of built-up areas. This disparity underscores the existence of ecological imbalances among urban subregions in Malang City. Consequently, strategically expanding urban green spaces, particularly in districts with the greatest oxygen deficits, is essential to promote sustainable urban environmental management.

Keywords: NDVI; biomass estimation; oxygen balance; urban green space; Klojen; Kedungkandang

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## Introduction

Oxygen is vital for sustaining life and maintaining ecological balance, especially in urban environments (Putra et al., 2025; Krstić et al., 2023). In urban ecology, oxygen also serves as an indicator of vegetation capacity in preserving air quality and urban well-being (Krstić et al., 2023). However, rapid population growth, increased transportation, and the conversion of green areas into built-up zones are significantly reducing the natural ability of cities to produce oxygen (Dzulfiqar et al., 2024). The imbalance between oxygen generated by vegetation and that consumed by humans, vehicles, and livestock can degrade air quality and reduce both thermal comfort and ecological carrying capacity (Fahreza et al., 2022). Therefore, regular analysis of oxygen balance is essential for understanding urban ecosystem health and guiding the planning and management of Green Open Spaces (GOS) (Astuti & Fardhani, 2020).

Malang City, as a key economic and educational center in southern East Java, faces growing ecological pressure due to rising population density and urban expansion. Data from Statistics Indonesia (BPS) show an average annual population increase of 0.9%, accompanied by

rapid expansion of built-up areas, especially in central and northern regions. The contrasting ecological profiles of Kedungkandang and Klojen districts highlight this dynamic: Kedungkandang retains extensive vegetated and agricultural land, while Klojen, as the city center, is characterized by dense settlements and intense economic activity. This contrast provides a unique opportunity to examine spatial variations in urban oxygen availability in relation to urbanization and green space distribution (Samsuri et al., 2021).

Given the challenges of field measurement in urban ecological monitoring, remote sensing technology especially Sentinel-2 satellite imagery has become an efficient, quantitative, and spatially explicit tool for estimating ecosystem oxygen production (Ludwig et al., 2021). The Normalized Difference Vegetation Index (NDVI), derived from multispectral sensors, directly correlates with photosynthetic activity and plant health, enabling large-scale and repeatable spatial assessment of vegetation's contribution to oxygen regeneration (Wibowo & Susilo, 2020). NDVI-based approaches are particularly useful in fragmented urban environments where pressure on ecosystem services is high (Krstić et al., 2023).

Previous studies in Malang have examined land-cover change, vegetation degradation, and carbon stocks, parameters that relate indirectly to oxygen production (Mbele & Setiawan, 2015; Madapuri et al., 2021; Hariyanto et al., 2024). Although carbon-stock assessments are widely used and have been extensively conducted in urban ecological studies (Suheriyanto et al., 2024), they

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primarily measure the amount of carbon stored in vegetation and therefore do not indicate whether the oxygen produced by vegetation is sufficient to meet anthropogenic oxygen demand. In contrast, oxygen-balance assessment integrates both oxygen availability and oxygen consumption, offering a more explicit indicator of ecological carrying capacity and urban atmospheric sustainability (Munawaroh et al, 2024). However, none of the previous studies in Malang explicitly quantified oxygen balance by combining vegetation-derived oxygen availability with oxygen consumption from humans, motor vehicles, and livestock. Furthermore, most analyses were conducted at the city scale, which tends to obscure spatial disparities among districts. By quantifying oxygen balance at the sub-district level, this study identifies localized ecological deficits and provides more actionable insights for targeted spatial planning. To our knowledge, this is the first study to quantify district-level oxygen balance in Malang City using remote sensing data, representing a novel contribution to the field. Additionally, the 2019–2024 temporal coverage, including the post-pandemic period, captures shifts in mobility, vehicle activity, and vegetation conditions that affect both oxygen demand and oxygen availability. This study therefore fills a critical research gap by integrating Sentinel-2 NDVI based oxygen availability with anthropogenic oxygen-demand calculations across humans, motor vehi-

cles, and livestock to provide a comprehensive district-level ecological assessment.

The current condition of Malang City highlights the urgent need to increase the proportion of GOS to improve air quality and strengthen urban ecological resilience. According to the Malang City Environmental Agency (2023), the total area of GOS remains below the 30% threshold mandated by Law No. 26 of 2007. This imbalance may intensify oxygen deficits, especially in densely populated areas like Klojen District. Therefore, this research aims to: (1) calculate oxygen demand based on human, vehicle, and livestock activities; (2) analyze oxygen availability using Sentinel-2 NDVI data; and (3) assess the oxygen balance in Klojen and Kedungkandang districts and propose policy recommendations. The findings provide a scientific foundation for urban spatial planning and a transferable framework for assessing oxygen balance in other cities, contributing to sustainable and resilient urban environments.

## Methods

### Study Area

This study was conducted in two districts of Malang City Kedungkandang and Klojen which represent distinct ecological characteristics and levels of urbanization.



**Fig. 1.** Klojen and Kedungkandang District

Figure 1 illustrates the study area, showing the spatial boundaries and contrasting land characteristics between Kedungkandang and Klojen Districts. Kedungkandang District covers an area of 39,89 km<sup>2</sup>, dominated by natu-

ral vegetation and agricultural land, particularly in the southern part (BPS Kota Malang, 2019-2024). In contrast, Klojen District, with an area of 8,83 km<sup>2</sup> (BPS Kota Malang, 2024), is characterized by dense built-up are-

as and minimal green spaces. The selection of these two locations was based on their contrasting proportions of built-up and vegetated land, allowing for the spatial analysis of oxygen balance across urban environments. The main analysis period spans 2019–2024, representing the most recent environmental dynamics and urban growth trends in Malang City.

**Data and Data Sources**

This research employed a spatially based quantitative approach integrating remote sensing and statistical data. The main dataset comprised Sentinel-2 Level-2A multi-spectral imagery, accessed and processed via the Google Earth Engine (GEE) platform. Images from 2019–2024 were selected with less than 20 percent cloud cover to ensure quality. GEE was utilized for its capacity to manage high-resolution satellite archives, perform automated atmospheric correction, and efficiently process extensive spatial data (Cardille et al., 2024). The workflow included atmospheric correction and cloud masking, clipping imagery to the administrative boundaries of Kedungkandang and Klojen (in shapefile format), generating annual median composites, and calculating NDVI (Normalized Difference Vegetation Index) using reflectance from Band 8 (842 nm, NIR) and Band 4 (665 nm, RED). Annual NDVI outputs were exported in GeoTIFF format for further analysis. NDVI classification using QGIS standardized value ranges and ensured consistent visualization of vegetation greenness across time, grouped into three density classes.

Secondary data from the Malang City Statistics Agency (BPS) for 2019–2024 included demographic, motor-vehicle, and livestock records, each compiled at the district level from the respective official sources. Preliminary data processing tabulation, normalization, and variable integration was performed in Microsoft Excel before conducting oxygen demand analysis to align biophysical and anthropogenic indicators across spatial units.

**Estimation of Oxygen Demand**

Oxygen demand was calculated based on total oxygen consumption by humans, motor vehicles, and livestock, expressed in tons per year, using the following general formula:

$$O_2 \text{ Demand} = O_2 \text{ Human} + O_2 \text{ Vehicle} + O_2 \text{ Livestock}$$

Human oxygen consumption was estimated using total population data multiplied by an average oxygen requirement of 0,864 kg O<sub>2</sub> per person per day (equivalent to approximately 315 kg O<sub>2</sub> per year), based on WHO (2021) and Munawaroh et al. (2024).

$$O_2 \text{ Human} = P \times 0,864 \times 365$$

where P represents the total population.

Vehicle-related oxygen consumption was calculated using the number of registered vehicles per district multiplied by oxygen consumption coefficients per vehicle type (Ministry of Public Works, 2008):

- Passenger car : 11,63 kg O<sub>2</sub>/day/unit
- Bus : 45,76 kg O<sub>2</sub>/day/unit
- Truck : 22,88 kg O<sub>2</sub>/day/unit
- Motorcycle : 0,58 kg O<sub>2</sub>/day/unit

$$O_2 \text{ Vehicle} = \sum (n_i \times c_i \times 365)$$

where n<sub>i</sub> is the number of vehicles by type, and c<sub>i</sub> is the oxygen consumption rate for each type.

Livestock oxygen consumption was estimated from the livestock population in each district using coefficients adapted from Daretamarlan et al. (2022):

- Cows : 1,70 kg O<sub>2</sub>/day/head
- Goat : 0,314 kg O<sub>2</sub>/day/head
- Chicken : 0,17 kg O<sub>2</sub>/day/head

$$O_2 \text{ Livestock} = \sum (n_j \times c_j \times 365)$$

where n<sub>j</sub> is the livestock population and c<sub>j</sub> is the oxygen consumption rate per animal. Although the livestock sector contributes relatively less oxygen demand compared to humans and vehicles, it was included in the analysis particularly because Kedungkandang has a large poultry population that significantly influences total oxygen demand.

**Estimation of Oxygen Availability**

Oxygen availability was estimated by converting NDVI values derived from Sentinel-2 imagery into vegetation biomass, which was then converted into carbon stock and annual oxygen production. This approach followed the empirical method developed by Munawaroh et al. (2024), assuming a positive linear correlation between NDVI and vegetation biomass. NDVI values were converted into biomass using the regression equation from Wiradharma (2014) dalam Munawaroh et al. (2024):

$$\text{Biomass} = 86,19 \times \text{NDVI} - 18,14$$

Negative results were set to zero, as areas with no vegetation are assumed to have no biomass. Biomass was converted to carbon stock using a conversion factor of 0,47 (SNI 7724:2011), indicating that approximately 47% of dry biomass mass consists of carbon:

$$C = \text{Biomass} \times 0,47$$

Carbon stock was converted to oxygen using the atomic weight ratio of carbon (12) and oxygen (32), following the photosynthesis equation (6CO<sub>2</sub> + 6H<sub>2</sub>O → C<sub>6</sub>H<sub>12</sub>O<sub>6</sub> + 6O<sub>2</sub>):

$$O_2 = C \times \frac{32}{12}$$

The results were expressed in tons per year for each district.

Oxygen production per pixel was aggregated within the administrative boundaries of Kedungkandang and Klojen to calculate total annual oxygen availability

(tons/year). Spatial processing was performed in Google Earth Engine, and NDVI maps were visualized using QGIS for interpretation and classification purposes.

NDVI-based oxygen estimates were processed in Google Earth Engine and visualized in QGIS, aggregated within Kedungkandang and Klojen boundaries. Visual validation used Google Earth Pro imagery, while biomass and oxygen values were cross-referenced with studies in similar tropical ecosystems (Munawaroh et al., 2024; Nugraha et al., 2022), confirming the robustness of the 2019–2024 oxygen production estimates and their relevance for assessing district-level ecological capacity.

## Results

### Overview of Demographic and Sectoral Data

The demographic and sectoral data obtained from Badan Pusat Statistik (BPS) provide an overview of the main components influencing oxygen demand in Kedungkandang and Klojen Districts during the 2019–2024 period. The compiled data include population figures, registered motor vehicles (cars, buses, trucks, and motorcycles), and livestock populations (cows, goats, and chickens), as presented in Table 1.

**Table 1.** Population, Vehicles, and Livestock Data, 2019–2024

Year	District	Population (persons)	Cars (Units)	Buses (units)	Trucks (units)	Motorbikes (units)	Cows (head)	Goats (head)	Chickens (head)
2019	Kedungkandang	220.055	17.454	150	3.702	104.320	1.460	714	140.690
2019	Klojen	111.053	13.689	297	3.954	57.607	0	0	1.680
2020	Kedungkandang	222.742	16.199	126	2.930	77.335	1.549	970	60.670
2020	Klojen	111.313	12.532	287	3.230	42.159	0	0	730
2021	Kedungkandang	225.337	13.958	93	760	60.421	1.471	1.150	71.410
2021	Klojen	110.796	10.606	240	988	32.431	0	0	690
2022	Kedungkandang	210.211	16.251	97	2.737	75.285	935	1.103	71.737
2022	Klojen	100.257	11.933	254	2.879	40.652	0	0	763
2023	Kedungkandang	214.157	14.165	84	2.129	58.441	904	1.192	47.169
2023	Klojen	100.712	10.327	222	2.365	30.256	0	0	669
2024	Kedungkandang	217.877	12.550	7	509	50.122	1.036	1.780	57.361
2024	Klojen	100.818	8.743	22	510	25.222	0	0	357

Source: BPS, Malang in Figures

The data show that Kedungkandang consistently records a larger population than Klojen throughout the observed period, despite a temporary decline around 2022, possibly due to post-pandemic population adjustments. Vehicle ownership generally declined in both districts, particularly for private cars and motorcycles, reflecting changes in registration and mobility behavior. Livestock populations remain significant in Kedungkandang, underscoring its semi-urban and agricultural characteristics, while Klojen dominated by built-up areas has almost no livestock. These contrasting patterns reflect distinct ecological and functional profiles within Malang City, forming the foundation for subsequent oxygen demand analysis.

### Overview of Oxygen Demand

The overview of oxygen demand in Kedungkandang and Klojen Districts is constructed from demographic, transportation, and livestock data obtained from Badan Pusat Statistik (BPS) covering the period of 2019–2024. These parameters represent the main anthropogenic and biotic factors influencing oxygen consumption in urban areas. The summary of population data, motor vehicle ownership (cars, buses, trucks, and motorcycles), and livestock population (cows, goats, and chickens) for each year is presented in Table 2.

**Table 2.** Oxygen Demand of Population, Vehicles, and Livestock, 2019–2024

Year	District	Population (persons)	Cars (Units)	Buses (units)	Trucks (units)	Motorbikes (units)	Cows (head)	Goats (head)	Chickens (head)
2019	Kedungkandang	69.396,54	74.091,36	2.505,36	30.916,14	22.084,54	907,00	81,83	8.575,76
2019	Klojen	35.021,67	58.109,12	4.960,61	33.020,64	12.195,40	0,00	0,00	102,40
2020	Kedungkandang	70.243,92	68.763,95	2.104,50	24.469,02	16.371,82	962,29	111,17	3.698,14
2020	Klojen	35.103,67	53.197,71	4.793,59	26.974,38	8.925,06	0,00	0,00	44,50
2021	Kedungkandang	71.062,28	59.251,01	1.553,32	6.346,91	12.791,13	913,83	131,80	4.352,80
2021	Klojen	34.940,63	45.021,94	4.008,58	8.250,99	6.865,64	0,00	0,00	42,06
2022	Kedungkandang	66.292,14	68.984,68	1.620,13	22.857,23	15.937,83	580,85	126,41	4.372,73
2022	Klojen	31.617,05	50.654,99	4.242,41	24.043,10	8.606,03	0,00	0,00	46,51
2023	Kedungkandang	67.536,55	60.129,72	1.403,00	17.779,70	12.371,96	561,59	136,62	2.875,19
2023	Klojen	31.760,54	43.837,60	3.707,93	19.750,59	6.405,20	0,00	0,00	40,78
2024	Kedungkandang	68.709,69	53.274,12	116,92	4.250,76	10.610,83	643,59	204,01	3.496,44
2024	Klojen	31.793,96	37.113,60	367,45	4.259,11	5.339,50	0,00	0,00	21,76

Source: BPS, Malang in Figures

Based on the compiled data, the relative contribution of each sector to the total oxygen demand varies across districts. In Kedungkandang, the human sector accounts for the largest share of total oxygen demand, reflecting the dominance of household consumption. In contrast, in Klojen, motor vehicles contribute a greater proportion due to the district's dense urban activities and high traffic intensity.

Overall, the descriptive data illustrate two distinct patterns of oxygen demanding activities within the same city. Kedungkandang's demand is primarily human and livestock-driven, while Klojen's is dominated by transportation and dense urban activity. These differences form an important foundation for understanding spatial variations in oxygen demand before quantifying their magnitudes in subsequent analyses.

### Temporal Interpretation and Driving Factors

Temporally, the oxygen demand trend from 2019 to 2024 shows noticeable fluctuations (Figure 2). Both Kedungkandang and Klojen experienced a decline in oxygen demand from motor vehicles after 2019, followed by a temporary rebound in 2022 and another decline in 2024 (BPS Kota Malang, Motor Vehicle Statistics 2019–2024). These shifts indicate that the pattern is not linear but influenced by interacting factors such as changes in vehicle registration, mobility restrictions during the COVID-19 pandemic, and varying economic activity levels affecting vehicle traffic intensity (Pratama et al., 2023; Marpaung et al., 2022).

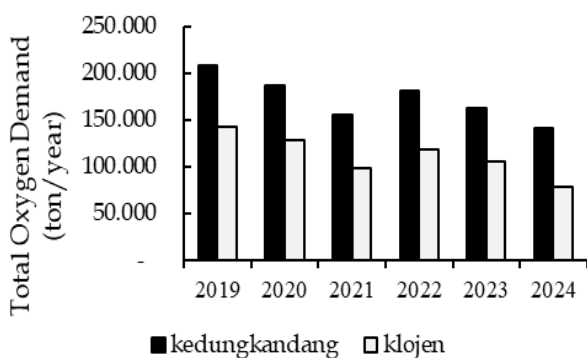


Fig. 2. Total Oxygen Demand

The 2024 decline, when Kedungkandang's total oxygen demand dropped to 141.306,36 tons from 162.794,33 tons in 2023, corresponds with a sharp reduction in registered vehicles (see vehicle dataset). A more significant decline occurred in Klojen due to its compact spatial area and high vehicle density per hectare, meaning that small changes in ownership can substantially affect oxygen consumption. However, lower oxygen demand does not automatically indicate ecological recovery if oxygen production from vegetation declines at a greater rate. This condition highlights the need for integrated oxygen balance analysis that jointly assesses oxygen consumption and generation within the same spatial framework (Monica & Ruchlihadiana, 2022).

From a spatial perspective, Kedungkandang's broad semi-urban area creates dispersed oxygen demand dominated by residential and agricultural activities (Purwanto, 2023). Conversely, Klojen's dense urban environment concentrates oxygen consumption in core zones dominated by transportation. These contrasting dynamics emphasize the spatial imbalance between anthropogenic pressure and ecological capacity, forming the analytical basis for evaluating the sustainability of urban oxygen equilibrium.

### NDVI Trends and Spatial Patterns

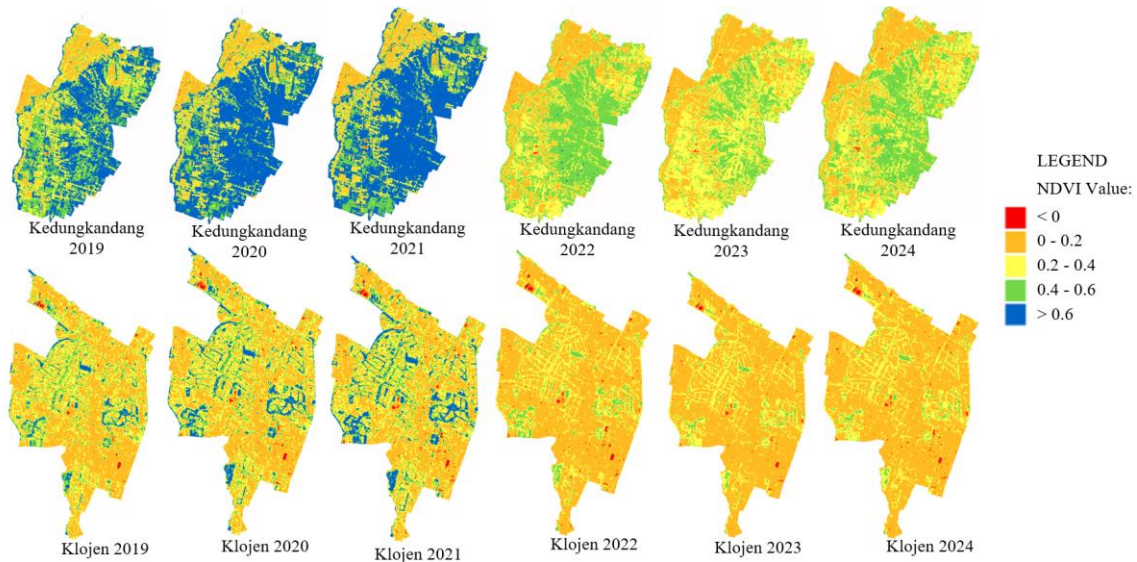
The annual NDVI composite (median values from Sentinel-2 imagery processed in Google Earth Engine) revealed consistent vegetation differences between Kedungkandang and Klojen during 2019–2024. Kedungkandang maintained relatively high NDVI means of 0,48–0,56 in 2019–2021, indicating healthy vegetation cover, but declined to 0,33–0,31 in 2022–2024. In contrast, Klojen consistently showed lower NDVI means of 0,25–0,28 in 2019–2021, dropping to 0,15–0,18 in later years, reflecting its dense urbanization and limited vegetation. The overall decline in both districts indicates reduced vegetation density and photosynthetic activity after 2021, likely linked to post-pandemic urban expansion, conversion of green land, and declining vegetation maintenance. Although semi-rural, Kedungkandang also experienced vegetation stress starting in 2022 (Purwanto, 2023), suggesting land-use pressure and decreased agricultural vitality.

Spatial analysis emphasized this contrast (Rushayati et al., 2025). In Kedungkandang, higher NDVI values clustered in southern zones, aligning with agricultural areas, riparian buffers, and connected vegetation corridors that enhance oxygen production and ecosystem resilience. Meanwhile, in Klojen, vegetation existed as scattered patches within parks, roadsides, and campuses, fragmented by impervious surfaces that reduced ecological connectivity. Figure 3 illustrates these disparities: Kedungkandang retains broad green continuity, while Klojen exhibits fragmented and shrinking vegetation. Overall, Kedungkandang shows relative ecological resilience, whereas Klojen continues to suffer green-space fragmentation and declining oxygen-generating capacity.

The sharp decline in NDVI observed during the 2022–2023 period, particularly in Klojen District, indicates notable ecological stress on vegetation cover. Several factors may have contributed to this degradation, such as increasing urban infrastructure development, land conversion of small green spaces into built-up areas, and temporary vegetation disturbances caused by pruning or seasonal drought (Purwanto, 2023). In highly urbanized areas like Klojen, where population density is high, the decline in NDVI reflects the shrinking capacity of green spaces to sustain their ecological functions.

### Estimation of Oxygen Availability Based on NDVI

Oxygen availability was estimated using the NDVI–biomass–carbon–oxygen conversion model developed by Munawaroh et al. (2024).



Source: Processed Sentinel-2 NDVI  
**Fig. 3.** Annual NDVI Maps of Kedungkandang and Klojen Districts (2019–2024)

**Table 3.** Estimated Biomass, Carbon Stock, and Oxygen Availability in Kedungkandang and Klojen Districts

Period	District	Total Biomass (ton)	Total Carbon Stock (ton C)	Oxygen Equivalent (ton O <sub>2</sub> )
2019	Kedungkandang	96.102,80	45.168,32	120.448,84
2019	Klojen	5.965,23	2.803,66	7.476,42
2020	Kedungkandang	120.511,73	56.640,52	151.041,37
2020	Klojen	7.345,69	3.452,47	9.206,59
2021	Kedungkandang	123.227,00	57.916,69	154.444,51
2021	Klojen	8.152,12	3.831,49	10.217,32
2022	Kedungkandang	51.522,38	24.215,57	64.574,71
2022	Klojen	2.295,37	1.078,83	2.876,87
2023	Kedungkandang	36.090,72	16.962,64	45.233,70
2023	Klojen	1.682,83	790,93	2.109,15
2024	Kedungkandang	43.838,99	20.604,32	54.944,86
2024	Klojen	1.809,74	850,58	2.268,21

Source: Processed Sentinel-2 NDVI

The tabulated results (Table 3) demonstrate that annual variations in NDVI are closely mirrored by changes in biomass and oxygen equivalent values, suggesting that vegetation productivity plays a significant role in oxygen supply. This pattern is especially evident in Kedungkandang, where annual peaks and declines in NDVI are reflected in corresponding biomass and oxygen outputs. In 2021, Kedungkandang produced approximately 123.000 tons of biomass, equivalent to 154.444 tons of O<sub>2</sub>, while Klojen generated only around 10.217 tons. Despite overall reductions in 2022–2023, Kedungkandang remained the primary oxygen contributor, exceeding Klojen by more than tenfold due to its extensive vegetated and agricultural landscape compared with Klojen’s dense urban environment. Overall, Kedungkandang acts as the “lungs

of the city,” supporting Malang’s air balance, while Klojen exhibits limited ecological capacity. Nevertheless, these results should be interpreted with caution, as NDVI–biomass conversion is empirical and affected by vegetation type, canopy structure, and seasonal variability. The 2022–2023 decline may also relate to temporary land-cover changes or image artifacts; thus, field validation and sensitivity tests ( $\pm 10\text{--}20\%$ ) are recommended to enhance model accuracy.

**Oxygen Balance: Surplus/Deficit and Ecological Equilibrium Analysis**

Oxygen balance, calculated as available O<sub>2</sub> minus required O<sub>2</sub>, reveals persistent ecological deficits in both districts. As shown in Table 4, Kedungkandang despite

**Table 4.** Annual Oxygen Balance in Kedungkandang and Klojen Districts (2019–2024)

Year	Kedungkandang Oxygen Demand (tons)	Kedungkandang Oxygen Availability (tons)	Kedungkandang Balance (tons)	Klojen Oxygen Demand (tons)	Klojen Oxygen Availability (tons)	Klojen Balance (tons)
2019	208.558,53	120.448,84	-88.109,69	143.409,86	7.476,42	-135.933,44
2020	186.724,80	151.041,37	-35.683,42	129.038,90	9.206,59	-119.832,31
2021	156.403,08	154.444,51	-1.958,56	99.129,83	10.217,32	-88.912,51
2022	180.772,02	64.574,71	-116.197,31	119.210,09	2.876,87	-116.333,22
2023	162.794,33	45.233,71	-117.560,62	105.502,63	2.109,15	-103.393,48
2024	141.306,36	54.944,86	-86.361,49	78.895,39	2.268,21	-76.627,17

its higher production, rarely achieves equilibrium. Its smallest deficit occurred in 2021 (−1.959 tons), but widened drastically in 2022–2023 (over −116.000 tons) before a modest recovery in 2024. Klojen consistently experienced severe deficits, from −135.933 tons in 2019 to −76.627 tons in 2024, due to its dense urban fabric and limited green areas.

The year 2021 exhibits a near-balance condition, likely reflecting short-term vegetation recovery or temporarily favorable land-use dynamics (Hasyim et al., 2025). However, subsequent years show sharp declines linked to post-pandemic construction, vegetation loss, and climatic stress. These findings indicate that while Kedungkandang remains crucial for citywide oxygen supply, its ecological capacity is increasingly threatened by land conversion and fragmentation. Klojen, meanwhile, depends heavily on green spaces in surrounding districts like Kedungkandang to compensate for its oxygen deficit (Purwanto et al., 2023).

### Policy and Practical Implications

Each district could adopt minimum oxygen-balance or green-space targets as part of sustainable urban planning indicators. Integrating NDVI-based ecological metrics into spatial planning (RDTR/RTRW) and establishing inter-agency coordination among environmental, spatial planning, and transportation sectors are crucial. For Klojen, government should prioritize the expansion of green infrastructure, including public parks, pocket greens, and street trees, supported by policy incentives for green roofs and vertical gardens (WHO, 2021). In Kedungkandang, protecting existing vegetated areas and improving agricultural vegetation management are essential to maintain its role as a key oxygen supplier (Monica & Ruchlihadiana, 2022).

Future research should improve NDVI–biomass calibration using local allometric data and integrate mobility datasets for more accurate oxygen-demand estimation. Incorporating landscape metrics like patch connectivity and fragmentation can clarify spatial efficiency in oxygen production. Scenario-based modelling such as simulating green-space expansion or vertical greening would help evaluate policy impacts. Findings from 2019–2024 highlight persistent oxygen deficits, underscoring the need for integrated greening and emission-reduction efforts to restore Malang’s urban ecological balance.

### Conclusion

This study confirms that Malang City experiences a persistent oxygen deficit from 2019–2024. Kedungkandang, though producing higher oxygen due to broader vegetation, still faces negative balances driven by population and transport-related demand. Klojen remains in chronic deficit because of limited green space and high urban density. The findings highlight the necessity of embedding oxygen-balance indicators into urban planning and expanding green infrastructure to restore ecological equilibrium and strengthen urban resilience.

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