Disturbed urban metabolism: ecological analysis of total suspended particulate (TSP) pollution load and the urgency of vegetation restoration on A.P. pettarani street, Makassar

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Abstract. A.P. Pettarani Street is a vital arterial road in Makassar City currently experiencing severe ecological pressure due to intensive anthropogenic activities. This study aims to analyze the pollution load of *Total Suspended Particulate* (TSP) and evaluate the environmental carrying capacity using a novel methodological approach: Ecological Synthesis. The research employs a descriptive quantitative design utilizing secondary data from 2023. The analysis focuses strictly on the metabolic interaction between traffic volume (energy input) and TSP concentration (metabolic residue). The results indicate that the air ecosystem has reached a saturation point, with TSP concentrations at four out of six sampling sites exceeding the National Ambient Air Quality Standard 230 µg/Nm^3. The highest concentration was recorded in the dense commercial segment (R Square), reaching 301.64 µg/Nm^3 The synthesis reveals a strong linearity (R^2=0.678) between vehicle volume and pollution levels, confirming an *ecosystem services deficit* where the natural assimilation capacity fails to neutralize the emission load caused by the dominance of motorcycles and the "canyon effect" of the elevated toll road. This study recommends ecological intervention through the restoration of stratified green belts to rebalance the urban ecosystem.

1 Introduction

1.1 Background

Urbanization is a global phenomenon that permanently alters the earth's surface, converting green spaces into impervious concrete landscapes. In Indonesia, the transformation of open spaces into built environments occurs at an exponential rate, often sacrificing ecological balance for economic acceleration. Makassar City, as the primary hub in Eastern Indonesia, faces significant environmental challenges due to rapid urban expansion and population growth. The city's metabolic rate defined by its consumption of energy and production of waste has accelerated beyond the natural environment's capacity to regenerate.

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One of the most tangible physical manifestations of this pressure is evident on A.P. Pettarani Street. This corridor functions as the city's economic spine, characterized by dense commercial and office areas. To address chronic congestion, an elevated toll road was inaugurated in 2021. While this infrastructure improved traffic flow, it paradoxically created a new ecological challenge: an emission tunnel that concentrates pollutants at the ground level. The physical structure of the elevated road acts as a barrier to vertical air mixing, trapping pollutants in the breathing zone of pedestrians and motorcyclists.
The most urgent environmental issue in this area is the decline in air quality due to *Total Suspended Particulate* (TSP). These dust particles are byproducts of a busy urban metabolism ranging from tire friction on asphalt and brake pad residues to crystallized exhaust emissions. The excessive presence of TSP in the atmosphere indicates a disruption in the urban ecosystem's material cycle. Unlike gaseous pollutants that may disperse rapidly, TSP tends to linger, creating a persistent haze that degrades the urban microclimate.

1.2 Research Urgency

The current condition of A.P. Pettarani Street reflects an imbalance between pollutant input and the environment's ability to self-purify. Existing studies often view traffic and pollution as separate statistical entities or focus solely on compliance with regulatory standards. This research introduces a novelty by applying Ecological Synthesis, viewing the street as a living ecosystem where vehicles represent "energy input" and TSP represents "waste residue".
This study aims to diagnose the metabolic efficiency of the street corridor by analyzing the correlation between traffic load and particulate accumulation. By understanding the linear relationship between the input (traffic) and the output (pollution), this research provides a scientific basis for green infrastructure planning, emphasizing the need to decouple urban mobility from environmental degradation.

2 Literatur Review

2.1 Urban Ecology and Carrying Capacity

In an ecological perspective, a city is viewed as a heterotrophic ecosystem that consumes vast amounts of energy and produces waste. Odum (1993) posits that urban ecosystems are inherently unstable because their material cycles are linear rather than circular [7]. The concept of *carrying capacity* in air pollution refers to the atmosphere's ability to disperse and neutralize pollutants without exceeding safety thresholds. When the emission rate from transportation (input) exceeds the natural assimilation rate provided by wind dispersion and vegetation deposition (processing), the ecosystem enters a state of "pollution saturation"[8].

2.2 Total Suspended Particulate (TSP)

TSP is defined as solid or liquid particles dispersed in the air with an aerodynamic diameter of less than 100 μm. In roadside environments, sources are classified into three metabolic byproducts:

a. Exhaust Emissions: Combustion residues, particularly soot from diesel engines and incomplete combustion from motorcycles.
b. Non-Exhaust Emissions: Particulates generated from mechanical wear. Harrison et al. (2021) note that tire wear, brake lining abrasion, and road surface erosion now contribute significantly to urban particulate burdens, often exceeding exhaust emissions in modern fleets [3].
c. Resuspension: The re-lifting of settled dust into the air due to the turbulence created by moving vehicles. Amato et al. (2019) describe this as a continuous cycle where the same particles are repeatedly suspended, maintaining high pollution levels even

when traffic flow decreases momentarily [13]. Previous theses, such as Halim (2016), have also highlighted how daily fluctuations in traffic correlate with these suspension events [14].

2.3 The Role of Vegetation as Bio-Filters

Vegetation serves as the primary mechanism for pollutant removal in urban settings. Trees and shrubs act as "bio-filters" or "ecosystem kidneys." Dahlan (2004) explains that plants mitigate TSP through:

- Adsorption: Trapping particles on rough, hairy, or waxy leaf surfaces.
- Airflow Modification: Reducing wind speed to facilitate the gravitational settling of dust [10]. The lack of vegetation along major corridors exacerbates the accumulation of TSP, as there is no biological sink to capture the emissions.

3 Research Methods

3.1 Research Design

This study employs a descriptive quantitative approach utilizing secondary data analysis. Unlike experimental research that relies on primary data collection, this study synthesizes empirical data previously published by Malik et al. (2023) [1] to provide a new perspective on urban ecosystem management. The approach is non-intrusive and focuses on re-interpreting existing datasets through the lens of urban ecology.

3.2 Data Source

The data are derived exclusively from the article *"Analyzing Total Suspended Particulate at AP Pettarani Street in Makassar City"*. The extracted data include:

1. Pollutant Data (Metabolic Residue): TSP concentrations measured via High Volume Air Sampler (HVAS) at six monitoring stations (R1–R6) along A.P. Pettarani Street.
2. Stressor Data (Energy Input): Daily traffic volume counts categorized by vehicle type: Motorcycles (MC), Light Vehicles (LV), and Heavy Vehicles (HV).

3.3 Data Analysis Technique: Ecological Synthesis

The novelty of this study lies in its Ecological Synthesis analysis technique. Instead of standard statistical description, this method interprets the data through the Urban Metabolism framework:

1. Input Analysis (Energy Flow): Traffic volume is analyzed as exogenic energy input. High traffic volume represents an energy overload that the local environment must process. The combustion of fossil fuels and the friction of tires are treated as energy releases into the micro-environment.
2. Output Analysis (Waste Generation): TSP concentration is analyzed as metabolic waste. The accumulation of TSP indicates the inefficiency of the system in managing its byproducts.
3. Efficiency Synthesis (Input-Output Correlation): The correlation coefficient (R Square) between traffic volume and TSP concentration is synthesized to determine the ecosystem's efficiency. A strong correlation in the absence of vegetation indicates a "leaky" ecosystem where waste accumulates rapidly due to a lack of filtration services. This linear regression analysis serves as the mathematical backbone for diagnosing the "ecosystem services deficit."

4 Result and Discussion

4.1 Anthropogenic Profile: The Energy Input

A.P. Pettarani Street functions as a high-energy corridor. The secondary data analysis indicates massive vehicle volumes, reflecting intense anthropogenic activity.

- Dominance of Motorcycles: Across all stations, motorcycles (MC) are the dominant mode of transport. At Point R2 (near Hertasning intersection), motorcycle volume peaked at 26,584 units/day, followed by light vehicles (LV) at 13,159 units/day.
- Total Metabolic Load: The heavy reliance on private motorized transport represents a significant fossil fuel energy input into the street's micro-environment. From an ecological standpoint, this continuous combustion process releases substantial thermal energy and particulate matter. The sheer volume of motorcycles, which often operate with less efficient combustion engines compared to modern cars, contributes disproportionately to the local pollution load. Sugiarto et al. (2020) have highlighted that motorcycles in Indonesian cities are major contributors to CO and HC, and by extension, particulate precursors [2].

4.2 Air Quality Status: Metabolic Waste Accumulation

The behavior of single-use plastic consumption is a tangible manifestation of anthropocentric arrogance. In this view, humans feel separate from and superior to nature, thus feeling entitled to exploit resources (petroleum for plastic) and dump the residue back into nature.

The analysis of TSP concentrations reveals that the ecosystem is struggling to process the waste generated by the traffic input. Based on converted 24-hour averages, the pollution profile is as follows:

- Point R2: 301.64 μg/Nm^3 (*Exceeds Standard*)
- Point R3: 248.26 μg/Nm^3 (*Exceeds Standard*)
- Point R1: 244.22 μg/Nm^3 (*Exceeds Standard*)
- Point R5: 233.62 μg/Nm^3 (*Exceeds Standard*)
- Points R4 & R6: Below the standard (208.36 and 183.93 μg/Nm^3)

Referring to the national standard of 230 μg/Nm^3, *66% (4 out of 6)* of the monitoring sites are in a state of failure [15]. Point R2, which corresponds to the highest traffic volume, exceeded the limit by approximately 31%. This indicates that the "waste removal" capacity of the atmosphere at these specific coordinates is insufficient to handle the "waste generation" rate of the vehicles. The atmosphere has become saturated, unable to dilute the pollutants effectively.

4.3 Ecological Synthesis: The Correlation of Degradation

The core of this study's novelty is the synthesis of the relationship between Input (Traffic) and Output (TSP).

- Statistical Evidence: The linear regression analysis yielded a Coefficient of Determination (R^2) of 0.678 with a significant p-value of 0.044.
- Ecological Interpretation: This statistic implies that 67.8% of the TSP variation is directly driven by vehicle dynamics. In a healthy ecosystem with adequate buffers (trees), this correlation might be weaker because vegetation would intercept a portion of the emissions. The strong linearity observed here confirms an Ecosystem Services Deficit. The street lacks the biological infrastructure to decouple traffic growth from pollution growth. Every additional unit of energy input (vehicle) translates almost directly into increased environmental degradation.

4.4 Discussion: Mechanisms of Saturation

Several ecological factors contribute to the high TSP levels observed, confirming the diagnosis of a disturbed urban metabolism:

1. The Non-Exhaust Factor: The high volume of motorcycles suggests that TSP is not just from exhaust soot, but significantly from tire wear and road abrasion caused by the sheer number of wheels in contact with the road surface. The "stop-and-go" nature of traffic in commercial areas (like R2) increases braking frequency, releasing brake dust containing heavy metals.
2. The Canyon Effect: The presence of the Elevated Toll Road acts as a physical lid on the street corridor. Oke et al. (2017) describe the urban canyon effect where vertical structures impede air mixing [11]. In Pettarani, the toll road structure likely traps pollutants generated by ground-level traffic, preventing them from dispersing into the upper atmosphere. This creates a "tunnel of pollution" where concentrations remain artificially high.
3. Resuspension Loop: With high traffic speeds and volume, the turbulence generated by vehicles continuously lifts settled dust back into the air [13]. Without vegetation to reduce wind speeds at the street level, this dust remains suspended, maintaining high TSP concentrations throughout the day.

4.5 Temporal Metabolic Fluctuations: The Heat-Pollution Nexus

The data reveals not only spatial variations but also significant temporal fluctuations in TSP levels, particularly peaking during the afternoon/noon hours (as seen in the R2 measurement of 598.74 $\mu g/Nm^3$ during peak sampling). This phenomenon can be explained through the Heat-Pollution Nexus.

- Atmospheric Stability: During midday, the asphalt surface of A.P. Pettarani absorbs solar radiation, creating a layer of hot air near the ground. Vallero (2014) explains that while heat usually induces convection (upward movement), the presence of the elevated toll road structure may suppress this natural chimney effect, creating a stable inversion layer that traps particulates close to the ground [12].
- Cumulative Buildup: The high afternoon readings reflect the cumulative metabolic residue of the day's activity. Unlike gases which may react or disperse, suspended particulates accumulate as traffic volume remains high throughout the workday. The "metabolic rate" of the street outpaces the removal rate, leading to a peak saturation point in the afternoon before subsiding in the evening. This suggests that the ecosystem has no recovery period during daylight hours.

4.6 The "Green Gap": Quantifying the Service Deficit

The critical missing component in A.P. Pettarani's ecosystem is the biological sink. The synthesis of high vehicle volume and high TSP is a direct symptom of the "Green Gap" the disparity between emission sources and absorption sinks.

- Lack of Deposition Surfaces: Nowak et al. (2006) demonstrated that urban trees remove large amounts of PM10 via leaf surface deposition [4]. The current landscape of Pettarani, dominated by concrete pillars and asphalt, offers negligible surface area for dust capture. The smooth surfaces of the infrastructure allow dust to remain airborne or be easily resuspended by wind, whereas rough bark and leaves would permanently trap a portion of this load.
- Thermal Regulation Failure: Vegetation also provides thermal regulation. Without shade trees, the high surface temperatures mentioned in section 4.5 exacerbate air

turbulence at the micro-level, keeping dust particles in a state of suspension. Siahaan et al. (2018) found that roads with dense canopy cover have significantly lower ambient temperatures and lower suspended dust levels due to increased humidity and reduced wind velocity [5]. The absence of this "cooling and calming" service is a major contributor to the TSP exceedances observed in this study.

5 Conclusion and Suggestions

5.1 Conclusion.

Based on the ecological synthesis of secondary data, this study concludes:

1. Ecological Failure: The air ecosystem of A.P. Pettarani Street is currently unable to sustain its metabolic load. Four out of six monitoring points exhibit TSP concentrations exceeding the environmental carrying capacity (>230 μg/Nm^3 indicating a state of severe pollution saturation.
2. Input-Output Linearity: There is a direct, unbuffered link (R^2=0.678) between vehicle energy input and pollution residue. This strong correlation confirms that the dominance of motor vehicles is the primary driver of environmental degradation.
3. Structural Deficit: The combination of high motorcycle volume, the physical barrier of the elevated toll road (Canyon Effect), and the lack of vegetation (Green Gap) has created a "saturation trap" for particulate matter.

5.2 Suggestions

To restore the ecological balance, the following interventions are proposed:

1. Vertical Ecological Restoration: Due to limited horizontal space, planting must focus on the vertical plane. Shade-tolerant plants (*Sansevieria*) should be planted extensively in the median under the toll road to absorb gaseous pollutants, while climbing plants could be utilized on toll road pillars to trap dust.
2. Road Ecology Management: Regular "street flushing" (washing the road surface) is necessary to break the cycle of dust resuspension, mimicking the natural cleaning function of rain.
3. Traffic Volume Control: Implementing restrictions on heavy vehicles during peak hours to reduce the abrasive load on the road surface and managing traffic flow to reduce stop-and-go emissions.

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