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ASSESSING PM2.5 EMISSION REDUCTION THROUGH COMMUNITY GREEN BEHAVIOR IN EAST JAKARTA: A SYSTEM DYNAMICS APPROACH

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Abstract

East Jakarta faces a severe $PM_{2.5}$ air quality crisis, with concentrations reaching 147.64 μg/m³ nearly ten times the national standard of 15 μg/m³. This study quantifies the potential of community green behavior to reduce $PM_{2.5}$ emissions through a system dynamics approach. Data from 100 respondents collected through proportional quota sampling were extrapolated to the East Jakarta household population (867,399 households) and incorporated into a Vensim PLE simulation model. The baseline inventory revealed total $PM_{2.5}$ emissions of 952.86 ton/year, dominated by the waste sector (85.6%), while vegetation absorbs only 102.78 ton/year, leaving a net deficit of 850.08 ton/year. The community Green Behavior Index (GBI) averaged 2.67 out of 5 (moderate); waste management registered the lowest GBI (2.30) despite its highest emission share, revealing a structural behavioral paradox. Four scenarios at moderate (GBI = 3.4) and optimistic (GBI = 4.2) intervention levels were simulated. The best case scenario achieved 23.36% emission reduction, with waste related behavior contributing 62.4% of that potential. Under the optimistic full sector scenario, emission absorption equilibrium is projected between 2035 and 2044, compared to approximately 2050 under Business as Usual. Green behavior is necessary but not sufficient; structural interventions remain essential.

Keywords: *$PM_{2.5}$ emission; green behavior; system dynamics; East Jakarta; air quality modeling*

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1. Introduction

Urban air pollution, particularly fine particulate matter ($PM_{2.5}$), poses one of the most urgent environmental health challenges in rapidly growing megacities (Hartono and Fitria 2023). $PM_{2.5}$ particles ≤2.5 µm in aerodynamic diameter penetrate deeply into the alveoli and enter the bloodstream, causing chronic respiratory and cardiovascular diseases (Aryanta and Maharani 2023). East Jakarta, the most densely populated municipality of DKI Jakarta with 3.31 million inhabitants, has recorded $PM_{2.5}$ concentrations reaching 147.64 µg/m³, far exceeding the national ambient standard of 15 µg/m³ (DLH 2025).

Three dominant behavioral emission sources drive this crisis (Fadhlurrahman 2024): (1) private vehicle use, with 3.19 million registered motorized vehicles (BPS

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2025); (2) household solid waste management, where open burning remains prevalent (Ramadan et al. 2023); and (3) household energy consumption from LPG and fossil fuel based electricity. Urban vegetation constitutes a fourth dimension, serving as a natural $PM_{2.5}$ sink through dry deposition on leaf surfaces. Together, these four sectors define the behavioral ecological nexus of $PM_{2.5}$ dynamics in the city (Zhang et al. 2022).

Prior studies have examined green behavior as a dimension of pro environmental lifestyle (Latifah et al. 2023; Ogiemwonyi 2024; Wu et al. 2022; Zhao et al. 2025; Subhaktiyasa 2024); and have inventoried urban emission sources (Hayyi and Apriani 2023; Hasan and katherin 2024). However, a quantitative integration of community behavioral indices into dynamic emission modeling remains scarce for Indonesian megacity contexts. Without quantified understanding of how behavioral change translates into emission reduction, policy interventions risk being directed toward low impact sectors.

The present study addresses this gap by: (1) estimating Business as Usual (BAU) $PM_{2.5}$ emissions across four community driven sectors; (2) measuring the community Green Behavior Index (GBI) using validated survey instruments; (3) modeling reduction potentials under four progressive intervention scenarios via system dynamics simulation; and (4) projecting the timeline to emission absorption equilibrium. The novelty lies in the empirical coupling of field measured behavioral data with a sector specific dynamic emission model an approach not previously applied to $PM_{2.5}$ management in Indonesian metropolitan contexts.

2. Method

The study was conducted in East Jakarta, DKI Jakarta Province, Indonesia (106.87°E, 6.22°S), covering all ten sub districts. Primary data were collected from 100 respondents determined via the Slovin formula (e = 10%) (Sahir 2021) and distributed proportionally across sub districts through proportional quota sampling. Respondents were adults (17–50 years) actively engaged in household activities (Budiaji et al. 2013).

A structured questionnaire using a 5 point Likert intensity scale assessed four GBI dimensions: transportation behavior, household energy use, waste management, and environmental greening (Subhaktiyasa 2024; Amanda et al. 2021). The instrument was pre tested on 30 respondents from Bekasi City. Validity was assessed via Pearson product moment correlation (r table = 0.361 for n = 30, α = 5%), and reliability via Cronbach's Alpha. All 18 items passed validation (r calculated range: 0.639–0.957, all above r table = 0.361; Cronbach's Alpha range: 0.776–0.954, all above 0.6).

$PM_{2.5}$ emissions were estimated using the Indonesian National Emission Factor approach (KLHK 2022), expressed as $E = A \times EF$, where A is the activity rate and EF is the sector specific emission factor (Rahmasari et al. 2023). Total sectoral emissions were obtained by multiplying the average household emission derived from the 100 respondent survey by the total number of East Jakarta households (867,399), acknowledging that this extrapolation introduces uncertainty that should be interpreted with caution (Alfarisi and salman 2024). Transportation emission factors were: gasoline (EF = 2 g/L), diesel (EF = 1.5 g/L), and LPG fuelled vehicles (EF = 0.5 g/L). Waste emissions used an open burning EF of 8.3 g/kg (Liu et al. 2016; Roden et al. 2022) Household energy emissions applied EF = 0.04 g/kWh (Guéret and Warnecke 2024; R.A., Sari, and Meidiana 2022). for electricity and EF = 0.01 g/kg for LPG cooking.

Vegetation absorption was calculated using the deposition rate method of (Zhang et al. 2022), expressed as $R = \Sigma(N_i \times DR_i)$, where DR_i is the size class deposition rate (small trees: 0.04 g/tree/day; medium: 0.11 g/tree/day; large: 0.27 g/tree/day). The total tree population was estimated at 2,016,844 trees (1,036,844 privately owned and 980,000 in public green spaces).

A Causal Loop Diagram (CLD) was constructed to map 17 variables and their causal relationships. The CLD captures one dominant balancing loop — Air Quality → Community Awareness → GBI → Emission Rate → Net $PM_{2.5}$ → Air Quality and one reinforcing driver: Population Growth → Sectoral Emissions.

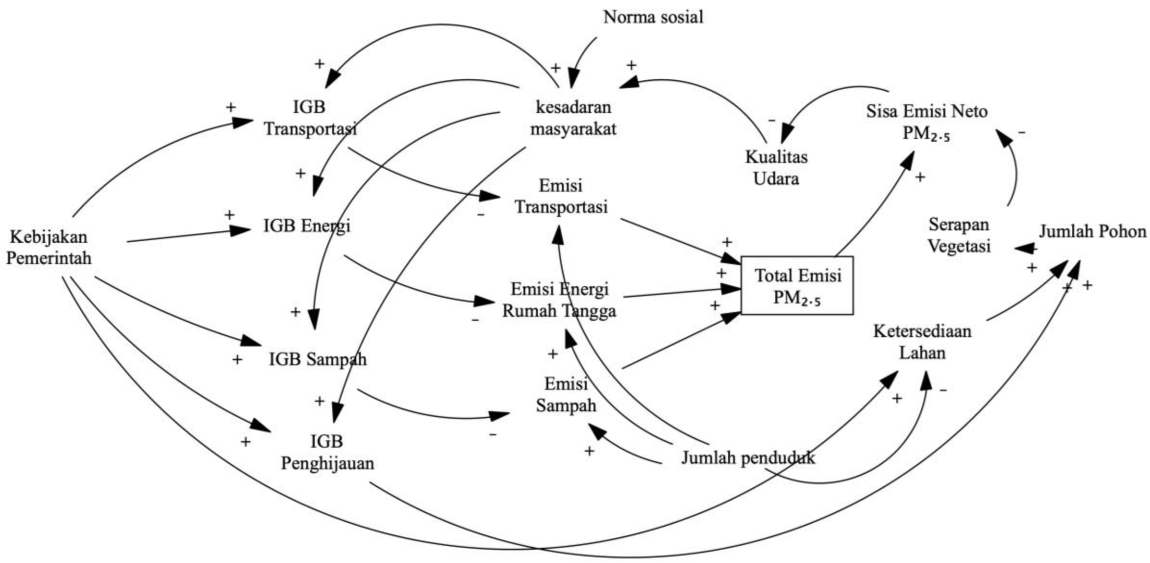

Figure 1. Causal Loop Diagram (CLD) of the $PM_{2.5}$ emission behavior system

The Stock and Flow Diagram (SFD) was implemented in Vensim PLE for 2026–2050 (time step = 1 year). Two stocks were defined: (1) Accumulated Net $PM_{2.5}$ and (2) Total Trees, growing at 10% per year from an initial stock of 2,016,844 trees, consistent with documented urban reforestation trends in DKI Jakarta. The sectoral emission rate under behavioral intervention was modeled as:

$$E_i = E^{AA} \times (1 - \alpha_i \times \Delta GBI\ /\ 5)$$

where α_i is the sector sensitivity coefficient (waste: 0.40; transportation: 0.35; energy: 0.20) and ΔGBI is the difference between the scenario target and the existing GBI (2.67). For the greening sector, intervention operates on the absorption side rather than the emission side: scenario greening targets increase the annual tree planting rate, directly augmenting absorption capacity without applying the emission reduction formula. BAU emissions grow at 0.26% per year, following East Jakarta's population growth rate. Model validity was confirmed through an Extreme Condition Test: GBI = 1 produced near maximum emissions, while GBI = 5 produced near zero net emissions.

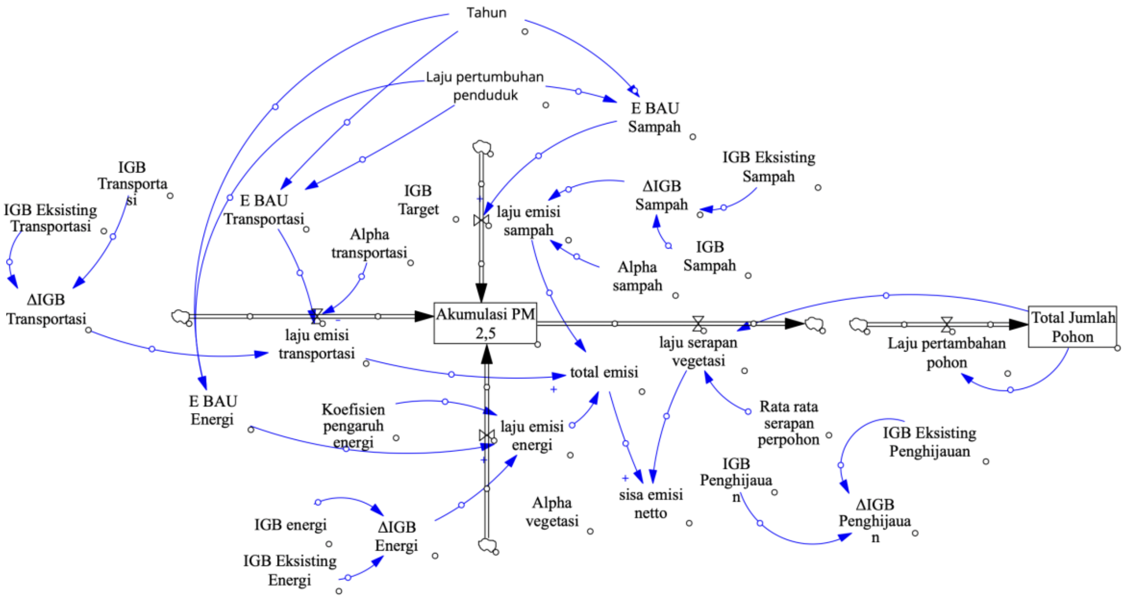

Figure 2. Stock and Flow Diagram (SFD) of the system dynamics model

Four cumulative scenarios were simulated at two GBI intensity levels (moderate target = 3.4; optimistic target = 4.2): S1, waste sector only; S2, waste and transportation; S3, waste, transportation, and energy; S4, all four sectors including greening. Greening scenarios increased the tree planting rate to accelerate absorption side reduction.

The system dynamics model implemented in Vensim PLE is deterministic; repeated simulations under identical parameters yield identical outputs (SD = 0). Model robustness was instead validated through Extreme Condition Testing

3. Result and Discussion

All 18 questionnaire items demonstrated strong validity across the four GBI dimensions (r calculated range: 0.639–0.957, all above r table = 0.361 for n = 30) and acceptable reliability (Cronbach's Alpha range: 0.776–0.954, all above 0.6). The transportation dimension exhibited the highest internal consistency (Alpha = 0.954), reflecting homogeneous behavioral patterns in vehicle use. The energy dimension showed the widest r calculated variation (0.648–0.795), consistent with heterogeneous household energy habits. All instruments were considered valid and reliable for use in the main survey.

The waste sector dominates total $PM_{2.5}$ emissions at 815.48 ton/year (85.6%), driven primarily by household open waste burning (EF = 8.3 g/kg) (Ramadan and Rachman 2022). This is consistent with studies identifying open burning as the primary $PM_{2.5}$ source in dense urban settlements (Febrianti and Anggraeny 2023). Transportation contributes 133.18 ton/year (14.0%), while household energy contributes only 4.20 ton/year (<0.5%), reflecting the effective suppression of domestic combustion emissions through LPG adoption (77% of respondents). Vegetation absorption of 102.78 ton/year covers 10.8% of total emissions, yielding a net deficit of 850.08 ton/year (emission to absorption ratio: 9.27:1).

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Table 1 presents the BAU emission inventory for East Jakarta in 2026.

Table 1. BAU $PM_{2.5}$ Emission Inventory, East Jakarta (2026)

Sector	Emission (ton/year)	Share (%)	Absorption (ton/year)
Transportation	133.18	14.0%	—
Household Energy	4.20	0.4%	—
Waste Management	815.48	85.6%	—
Vegetation (Sink)	—	—	102.78
Total Emission	**952.86**	**100%**	**—**
Net Emission (BAU)	**850.08**	**—**	**—**

A critical behavioral paradox emerges from Table 2: the highest GBI score (energy, 2.90) corresponds to the lowest emission share (0.4%), while the lowest GBI (waste, 2.30) corresponds to the highest emission share (85.6%). This inverse relationship reflects decades of public campaigns targeting vehicle emissions and energy efficiency, which have shaped behavioral awareness in lower impact sectors while leaving waste management largely unaddressed (Karliansyah et al. 2020).

Table 2. Green Behavior Index by Sector and Corresponding Emission Contribution

Sector	GBI Score	Category	Emission Share (%)
Transportation	2.87	Moderate	14.0%
Household Energy	2.90	Moderate	0.4%
Waste Management	2.30	Low	85.6%
Greening	2.62	Moderate	—
Overall Average	**2.67**	**Moderate**	**—**

Within waste management, the attitude behavior gap is particularly stark: the recycling and 3R practice indicator scored 1.77 (very low), and waste burning avoidance scored 1.87 (low), despite respondents generating 1.62 kg of waste per person per day. In the greening dimension, awareness of trees' role in $PM_{2.5}$ reduction scored 4.77 (very high), yet actual tree ownership scored only 1.87 (low), with 55 of 100 respondents owning no trees a gap attributable to structural constraints such as land scarcity in dense settlements rather than motivational deficits (Naftalia and Amalia 2025).

Four cross cutting findings emerge from the simulation. First, waste is the dominant driver: of the 23.36% maximum reduction in S4 Optimistic, 14.58 percentage points are attributable to waste behavioral change alone (S1 Optimistic), representing 62.4% of total reduction potential. This reflects waste's structural dominance at 85.6% of total emissions and the high emission factor of open burning relative to other sources.

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Second, intervention depth outperforms breadth on the critical sector. S1 Optimistic (14.58%, waste only) achieves 5.55 percentage points more reduction than S3 Moderate (9.03%, three sectors). This challenges the assumption that broader multi sector intervention is always superior; in systems with one dominant emission variable, sector specific intensity yields greater returns (Karliansyah et al. 2020).

Third, greening interventions deliver leverage through the absorption side of the system. The marginal gain from S3 to S4 at the optimistic level (7.29 percentage points) is the single largest gain from any individual sector addition. Because greening operates on the absorption outflow rather than the emission inflow, it functions as a high leverage intervention point in system dynamics terms.

Fourth, green behavior alone cannot resolve the structural disequilibrium. Even under S4 Optimistic, net emissions of 651.53 ton/year remain 76.6% of the BAU burden. Structural interventions including a prohibition on open waste burning, alternative waste processing infrastructure, electrification of public transport, and institutionally managed urban greening programs are essential complements to behavioral strategies.

Table 3 presents simulation results for all eight scenario intensity combinations against BAU.

Table 3. Simulation Results: Net $PM_{2.5}$ Emission by Scenario

Scenario	Active Sectors	Level	Net Emission (ton/yr)	Reduction from BAU (%)
BAU	—	—	850.08	0%
S1	Waste	Moderate	778.32	8.44%
S1	Waste	Optimistic	726.13	14.58%
S2	Waste + Transport	Moderate	773.38	9.02%
S2	Waste + Transport	Optimistic	713.73	16.04%
S3	Waste + Transport + Energy	Moderate	773.30	9.03%
S3	Waste + Transport + Energy	Optimistic	713.51	16.07%
S4	All Sectors	Moderate	742.70	12.63%
S4	**All Sectors**	**Optimistic**	**651.53**	**23.36%**

Regarding temporal dynamics: under BAU, natural tree stock growth (10% per year) drives vegetation absorption from 102.78 ton/year (2026) to 962.85 ton/year (2050), narrowing the net emission gap to approximately 51.29 ton/year by 2050 but not achieving equilibrium within the simulation period (Santoso et al. 2021). Under S4 Optimistic, emission absorption balance is projected between 2035 and 2044. Under S1 Optimistic (waste only), equilibrium is projected around 2045. These projections are derived from the Vensim model's annual stock flow outputs and underscore the long term strategic value of sustained community greening programs.

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4. Conclusion

This study presents an empirically grounded behavioral dynamic model of $PM_{2.5}$ emissions in East Jakarta, integrating field measured Green Behavior Index data into a validated system dynamics framework. Four principal findings emerge.

First, East Jakarta's $PM_{2.5}$ system is in severe structural disequilibrium: total emissions of 952.86 ton/year against an absorption capacity of 102.78 ton/year (ratio 9.27:1), with waste management accounting for 85.6% of the emission burden. Second, the community GBI of 2.67/5 (moderate) conceals a critical paradox the highest behavioral engagement occurs in the lowest emission sector (energy, GBI = 2.90), while the lowest engagement occurs in the highest emission sector (waste, GBI = 2.30). Third, the maximum achievable behavioral reduction is 23.36% (S4 Optimistic), with waste contributing 62.4% of that potential and greening providing absorption side leverage. Fourth, under the optimistic full sector scenario, emission absorption equilibrium is projected between 2035 and 2044, while BAU approaches equilibrium only around 2050; green behavior is necessary but not sufficient, requiring structural complements to close the remaining 76.6% deficit.

Policy recommendations include: (a) prioritization of behavioral transformation in waste management through community based enforcement and 3R infrastructure investment (Suryani 2024); (b) incentive programs for private tree planting in high density residential areas; and (c) reorientation of environmental communication from energy efficiency toward waste management, where behavioral change delivers empirically larger air quality impacts. Future research should incorporate meteorological dispersion modeling, extend temporal resolution to seasonal emission cycles, validate against multi year $PM_{2.5}$ monitoring data, and quantify the uncertainty bounds of the household level extrapolation to strengthen the predictive reliability of the behavioral emission coupling framework.

AI Writing Statements

The authors confirm that no generative AI or AI-assisted tools were used in the writing, translation, analysis, or preparation of this manuscript.

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