

PCOMMUNITY EDUCATION ON GREEN BELT STRUCTURING AND PARTICIPATORY ENVIRONMENTAL QUALITY MONITORING AROUND COAL-FIRED POWER PLANT X

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Abstract

Coal-fired power plants secure baseload electricity but expose neighbouring settlements to fly ash, stockpile dust, flue gases (SO₂, NO_x) and noise, while residents are usually treated as passive recipients of these impacts and have no means of checking air quality themselves. This participatory action research designed, implemented and evaluated an education programme on multi-strata green belt structuring and citizen-science environmental monitoring for communities around Coal-Fired Power Plant X. A one-group pretest–posttest design was combined with Participatory Action Research involving 40 residents from farmer groups, youth organisations and health cadres. Activities covered pollutant-tolerant species selection, canopy zoning, assembly of dustfall jars, operation of low-cost IoT particulate sensors and planting of a 300 m demonstration buffer. Knowledge scores were analysed with a paired-sample t-test and normalized gain. Mean scores rose from 42.00 ± 10.8 to 83.10 ± 7.1 ($p < 0.001$), with an N-gain of 0.71 (high category). Resident-led monitoring during follow-up recorded dustfall 41.1% lower in the nearest zone behind a 40–50% porosity barrier dominated by *Casuarina equisetifolia*, *Samanea saman* and *Terminalia neotaliala*. Combining ecological education with simple monitoring instruments enabled residents to act as independent, credible environmental monitors and to take part in evidence-based dialogue with the plant operator.

Keywords: Air quality; Citizen science; Coal-fired power plant; Green belt; Participatory monitoring

INTRODUCTION

Coal-fired power plants (CFPPs) remain the backbone of baseload electricity supply in many developing countries, Indonesia among them. The scale of coal combustion involved, however, carries complex ecological and public-health consequences (Haryanto, 2018). Stack emissions and fugitive emissions from open coal stockpiles release fine particulate matter with an aerodynamic diameter of 2.5 µm or less (PM_{2.5}), coarse particulates (PM₁₀), fly ash and bottom ash, together with acid precursor gases such as sulfur dioxide (SO₂) and nitrogen oxides (NO_x). The heaviest share of this burden falls on people living in the so-called Ring 1 area, within 0–2 km of the plant fence. Chronic exposure to coal dust and aerosol particulates is associated with a higher prevalence of acute respiratory infections, reduced lung function, bronchial asthma and cardiovascular disease, particularly among children and the elderly (World Health Organization, 2021). Daily life is affected as well: black soot settles on floors, contaminates open water sources and damages home-garden plants, and the microclimate around the industrial area becomes warmer.

In practice, greening programmes around CFPPs often fail for two reasons. First, they tend to be run as ceremonial corporate social responsibility (CSR) events, without adequate site-level ecological analysis and without substantive involvement of local residents. Seedling mortality is consequently high, because nobody in the community feels a sense of ownership over the trees. Second, environmental information is distributed very unevenly between the plant operator and the affected community. Power plants operate under technical approval and operational feasibility requirements for pollution control (Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2021) and are generally equipped with a Continuous Emission Monitoring System (CEMS) and automatic ambient air-quality stations, yet the data are technical, held internally and difficult for lay residents to access. When residents complain about thick dust, the complaint is commonly dismissed on the grounds that “air quality is still below the national standard”. The result is long-standing distrust and recurring social friction. This study responds to those cognitive, practical and institutional gaps among communities living around CFPP X. It has three aims: (1) to assess how effectively an education programme on multi-strata green belt structuring and monitoring

instrumentation improves residents' knowledge, using a comparative significance test and normalized gain (N-gain); (2) to formulate a participatory green belt design based on local plant species that tolerate coal-dust stress; and (3) to examine residents' own ambient air monitoring data (dustfall rate and PM_{2.5} concentration) at several distances from CFPP X before and after the vegetative buffer was planted.

LITERATURE REVIEW

Green Belts as Ecological Shields

Among nature-based mitigation options, the green belt or vegetative buffer zone is one of the best tested and most cost-efficient. A green belt is more than a landscape feature; it works as an aerodynamic barrier and a biophysical trap for pollutants (Janhäll, 2015; Tiwary et al., 2008). Through inertial impaction, direct interception and turbulent diffusion, tree canopies capture airborne dust and deposit it on leaf cuticles, twigs and bark.

How well a green belt performs depends heavily on its structure and on the species planted. Monoculture stands or rows that are too dense (porosity < 20%) behave like a solid wall: they generate a leeward vortex that drives particulates downward, straight into the settlement (Morakinyo & Lam, 2016). A multi-strata design, which combines tall canopy trees, mid-storey trees and dense understorey shrubs at an aerodynamic porosity of 40–50%, allows air to be filtered continuously without excessive turbulence (Beckett et al., 2000; Sæbø et al., 2012). Leaf traits matter as well. Species with trichomes (fine hairs), thick wax layers and rough surfaces retain considerably more dust than species with smooth, waxy leaves (Prusty et al., 2005).

Citizen Science and Community-Based Monitoring

Citizen science, also described as community-based environmental monitoring, has been put forward as a way to democratise environmental science and to narrow the information gap between industry and its neighbours (Conrad & Hilchey, 2011; Buytaert et al., 2014). Equipped with affordable tools such as low-cost sensors and simple dust deposition methods, residents can collect valid empirical evidence on their own. Gabrys et al. (2016) argue that when citizens hold their own environmental data (data citizenship), their bargaining position changes: they are no longer seen as “emotional complainers” but as partners in a constructive dialogue grounded in scientific evidence.

The literature therefore points to two elements that greening programmes around power plants rarely combine: a green belt designed on aerodynamic and ecological grounds, and a community able to verify its effect with its own measurements. This study addresses that gap by bringing both into a single participatory programme.

METHOD

Research Design

The study used Participatory Action Research (PAR) combined with a quantitative pre-experimental one-group pretest–posttest design. PAR was chosen because it rests on a repeated cycle of initial reflection, joint planning, field action, structured observation and continuous evaluation (Kemmis et al., 2014). Under this approach residents are not research objects but co-researchers who design and carry out mitigation actions in their own neighbourhood. Cognitive effectiveness was tested with the model $O_1 \rightarrow X \rightarrow O_2$, where O_1 is the baseline measurement (pre-test), X is the treatment, consisting of a thematic education package and structured technical workshops, and O_2 is the measurement after the intervention (post-test).

Study Site

The programme took place in Karanganyar Village, a Ring 1 area located 300–1,500 m south-west of the CFPP X complex. Wind rose analysis from the local meteorological station over the past five years shows that the prevailing dry-season wind blows from the north-east to the south-west. The settlement therefore lies directly in the dispersion path of the stack plume and of fugitive dust from an open coal stockpile with a capacity of 250,000 tonnes. The site is 0–15 m above sea level and has a dry tropical coastal climate, with a mean relative humidity of 72% and ambient temperatures of 28–35 °C.

Participants

Forty participants (N = 40) were selected by purposive sampling. The inclusion criteria were: (1) permanent residence in the Ring 1 area of CFPP X for at least five consecutive years; (2) membership of a strategic local group, namely farmer or community-forest groups (35%), the Karang Taruna youth organisation (30%), environmental health or PKK cadres (25%), and village officials or community leaders (10%); and (3) commitment to attend all classroom workshops, the field planting and the periodic self-monitoring.

Intervention Stages

The intervention ran intensively for eight weeks and was divided into four stages.

Stage 1: baseline assessment and participatory mapping (week 1). A pre-test was administered to gauge residents' initial literacy. In parallel, participatory mapping was used to identify the corridors along which coal dust travels, the points where soot accumulates most heavily, and degraded land along the industrial boundary that could be developed into a green belt corridor.

Stage 2: thematic workshops and hands-on training (weeks 2–3). Material was delivered interactively using an adult-learning (andragogy) approach and covered three modules: Module A, green belt bio-ecology and the optimum canopy porosity of 40–50%; Module B, multi-strata design in a staggered pattern of tall canopy trees, medium trees and understorey shrubs; and Module C, participatory monitoring instrumentation, including the assembly of dustfall jars and the operation of optical dust sensors.

Stage 3: field planting and installation of monitoring equipment (weeks 4–5). A demonstration green belt 300 m long and 15 m wide was established along the perimeter between the settlement and the plant, and 450 multi-strata seedlings were planted collectively. Residents installed three self-monitoring stations at different distances: Zone 1 (300 m from the plant, at the boundary), Zone 2 (700 m, core settlement) and Zone 3 (1,200 m, outer village boundary).

Stage 4: follow-up monitoring, post-assessment and institutionalisation (weeks 6–8). Residents took turns recording daily dustfall data and PM_{2.5} concentrations. At the close of the programme the post-test and a self-efficacy questionnaire were administered, and a forum of independent community environmental monitors was formed.

Instruments and Measurement

Data were collected with three instruments. The first was a cognitive literacy test of 10 multiple-choice items whose validity and reliability had been tested (KR-20 = 0.842). The second was dustfall measurement following SNI 19-7119.3-2005, using cylindrical deposition jars 20 cm in diameter exposed for 30 calendar days, with results expressed in ton/km²/month. The third was PM_{2.5} mass concentration, measured with a portable optical sensor (laser particle counter) cross-calibrated against a High Volume Air Sampler (HVAS).

Data Analysis

Quantitative data were processed in SPSS version 26.0 and Python 3.11. Normality was checked with the Shapiro–Wilk test, and pre- and post-intervention scores were compared with a paired-sample t-test at a significance level of $\alpha = 0.05$. The normalized gain was calculated following Hake (1998):

$$g = (S_{\text{post}} - S_{\text{pre}}) / (S_{\text{max}} - S_{\text{pre}}) \quad (1)$$

where g is the normalized gain, S_{post} and S_{pre} are the post-test and pre-test scores, and S_{max} is the maximum possible score. Gains were classified as high ($g \geq 0.70$), medium ($0.30 \leq g < 0.70$) or low ($g < 0.30$).

RESULTS AND DISCUSSION

Participant Characteristics

Table 1 summarises the socio-demographic profile of the 40 participants. Most were of productive age, 26–45 years (60.0%), and worked mainly as farmers or farm labourers (40.0%) or as factory and casual workers (32.5%). More than half had completed senior secondary education (55.0%), which gave them sufficient basic literacy to take up the citizen-science skills taught in the programme.

Table 1. Demographic characteristics of programme participants

Parameter	Category	Participants (n)	Percentage (%)
Sex	Male	25	62.5
	Female	15	37.5
Age group	Young (18–25 years)	9	22.5
	Young adult (26–45 years)	24	60.0
	Older adult (> 45 years)	7	17.5
Education	Primary (SD/SMP)	12	30.0
	Secondary (SMA/SMK)	22	55.0
	Tertiary (diploma/bachelor)	6	15.0
Livelihood	Farmer / farm labourer	16	40.0
	Self-employed / trader	8	20.0
	Factory / casual worker	13	32.5
	Housewife / PKK cadre	3	7.5
Distance from home to plant	Near zone (< 500 m)	18	45.0
	Middle zone (500–1,000 m)	14	35.0
	Far zone (> 1,000 m)	8	20.0

Participatory Green Belt Design and Species Selection

Based on the participatory mapping, residents agreed on a 300 m demonstration corridor planted in three staggered rows (triangular staggered arrangement) with an average canopy porosity of $45\% \pm 5\%$. The local species selected, together with their morphological and ecological characteristics, are listed in Table 2.

Table 2. Selected green belt species and their ecological characteristics

Canopy stratum	Species (local name)	Leaf morphology	Main ecological function	Spacing
Stratum 1 (upper; height > 10 m)	Casuarina equisetifolia (cemara udang)	Reduced needle-like leaves, deep stomatal grooves, thick cuticle	Windbreak; filters coastal and stack dust	3 m × 3 m
	Samanea saman (trembesi)	Wide, dense umbrella canopy; high stomatal density	Lowers microclimate temperature; traps dust aerosols; absorbs CO ₂	6 m × 6 m
Stratum 2 (middle; height 3–10 m)	Terminalia neotaliala (ketapang kencana)	Tiered horizontal branching; dense, waxy foliage	Filters dust flow at the roof height of houses	3 m × 3 m
	Swietenia macrophylla (broad-leaf mahogany)	Rough-textured leaf surface; tolerant of acid gases and drought	Dampens plant machinery noise; traps PM ₁₀	4 m × 4 m
Stratum 3 (lower; height < 3 m)	Bambusa multiplex (miniature Japanese bamboo)	Dense clumps; finely hairy leaf surface (trichomes)	Holds back fugitive dust moving along the ground	Dense, 0.5 m
	Sansevieria trifasciata (lidah mertua)	Thick, upright succulent; high tolerance of SO ₂	Binds ground-level particles; improves boundary soil	Dense, 0.3 m

Improvement in Residents' Knowledge

The Shapiro–Wilk test showed that the scores were normally distributed ($p = 0.214$ for the pre-test and $p = 0.187$ for the post-test; $p > 0.05$). The paired-sample t-test showed significant increases in every competency

dimension (Table 3 and Figure 1). The cumulative total score rose from 42.00 ± 10.8 to 83.10 ± 7.1 ($t = 25.76$, $p < 0.001$).

Table 3. Pre-test and post-test scores by competency dimension (N = 40)

Competency dimension	Pre-test (mean $\pm$ SD)	Post-test (mean $\pm$ SD)	Difference (Δ)	t	p-value
D1: Characteristics of plant emissions and pollutants	48.50 $\pm$ 11.2	82.50 $\pm$ 8.4	+34.00	16.84	< 0.001*
D2: Green belt bio-ecology and species selection	42.00 $\pm$ 12.5	87.00 $\pm$ 7.6	+45.00	21.52	< 0.001*
D3: Multi-strata architecture and arrangement	39.50 $\pm$ 10.8	84.50 $\pm$ 8.1	+45.00	23.10	< 0.001*
D4: Participatory monitoring (citizen science)	35.50 $\pm$ 14.1	80.00 $\pm$ 9.2	+44.50	18.96	< 0.001*
D5: Data-based advocacy and regulation	44.50 $\pm$ 13.0	81.50 $\pm$ 8.8	+37.00	17.43	< 0.001*
Cumulative total score	42.00 $\pm$ 10.8	83.10 $\pm$ 7.1	+41.10	25.76	< 0.001*

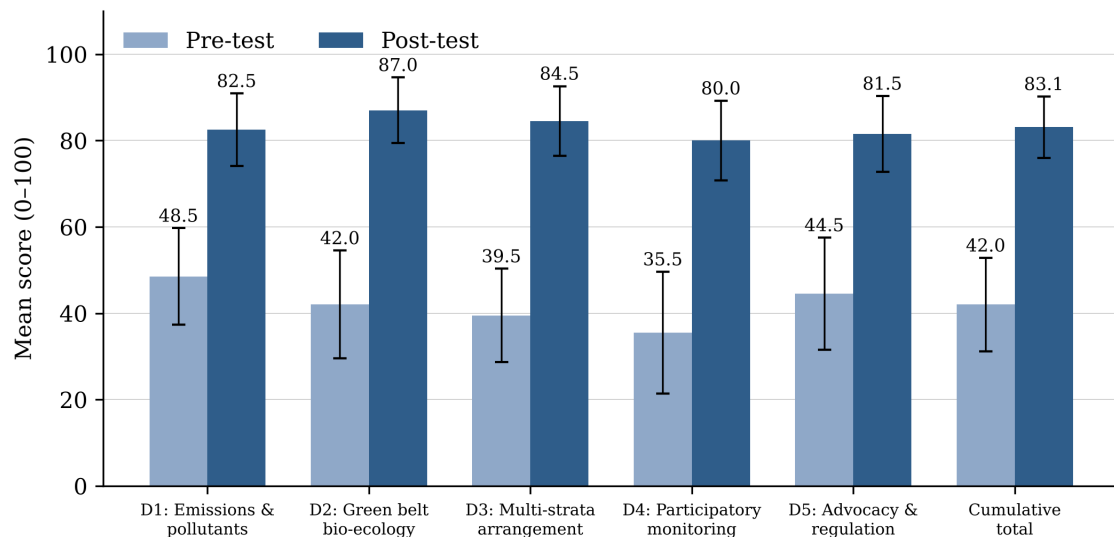


Figure 1. Pre-test and post-test environmental literacy scores by competency dimension (N = 40, $p < 0.001$); error bars show the standard deviation

The normalized gain analysis placed the programme in the high-effectiveness category, with an average of $\langle g \rangle = 0.71 \pm 0.10$. Twenty-six participants (65.0%) reached the high category and 14 (35.0%) the medium category, while none fell into the low category (Table 4 and Figure 2).

Table 4. Distribution of knowledge-gain categories based on N-gain

Gain category	Range (g)	Frequency (n)	Percentage (%)	Interpretation
High	$g \geq 0.70$	26	65.0	Very effective
Medium	$0.30 \leq g < 0.70$	14	35.0	Moderately effective
Low	$g < 0.30$	0	0.0	Not effective
Overall mean gain	$\langle g \rangle = 0.71 \pm 0.10$	40	100.0	High category

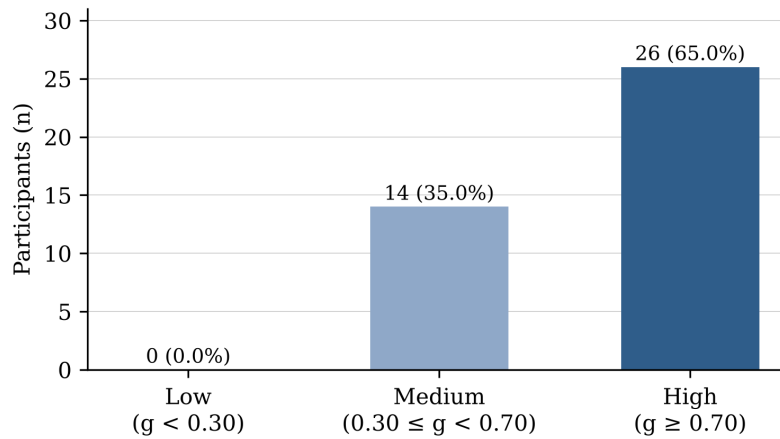


Figure 2. Distribution of participants across N-gain categories (N = 40)

Participatory Ambient Monitoring Results

Measurements taken by residents showed clear decreases in both dustfall and $PM_{2.5}$ after the green belt was established (Table 5 and Figure 3). In Zone 2 (core settlement, 700 m), dustfall fell by 40.5%, from 15.8 to 9.4 ton/km²/month, which brought it below the limit set in Government Regulation No. 22 of 2021 (< 10 ton/km²/month; Pemerintah Republik Indonesia, 2021). In Zone 1 (300 m), $PM_{2.5}$ dropped by 37.0%, from 58.3 to 36.7 $\mu\text{g}/\text{Nm}^3$.

Table 5. Results of residents' participatory air-quality measurements at different distances

Parameter	Monitoring point	Before buffer	After buffer	Reduction (%)	Standard (GR 22/2021)
Dustfall rate (ton/km ² /month)	Zone 1 (300 m, plant boundary)	22.4 ± 2.8	13.2 ± 1.6	-41.1	10.0
	Zone 2 (700 m, core settlement)	15.8 ± 2.1	9.4 ± 1.2	-40.5	10.0
	Zone 3 (1,200 m, outer boundary)	8.6 ± 1.4	5.7 ± 0.9	-33.7	10.0
Fine particulate $PM_{2.5}$ ($\mu\text{g}/\text{Nm}^3$, 24-hour)	Zone 1 (300 m, plant boundary)	58.3 ± 6.5	36.7 ± 4.2	-37.0	55.0
	Zone 2 (700 m, core settlement)	44.1 ± 5.1	27.2 ± 3.6	-38.3	55.0
	Zone 3 (1,200 m, outer boundary)	28.5 ± 3.9	19.8 ± 2.7	-30.5	55.0

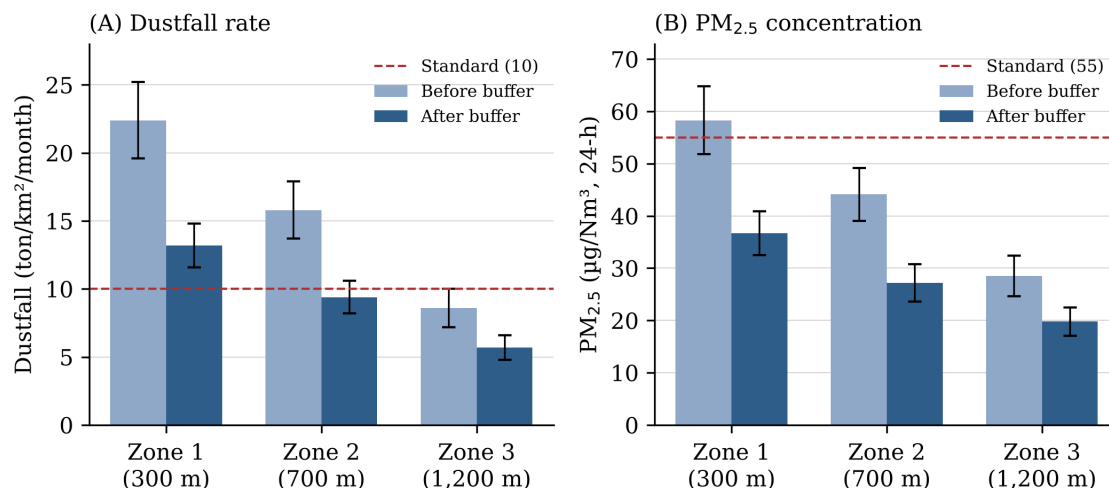


Figure 3. Residents' participatory ambient air measurements at different distances from CFPP X: (A) dustfall rate; (B) PM_{2.5} concentration

Experiential Learning and Knowledge Gains

An N-gain of 0.71 suggests that combining PAR with adult learning grounded in direct experience (the experiential learning cycle) achieves considerably more than conventional one-way outreach. In the environmental extension sessions usually organised by companies or government agencies, villagers are positioned as passive listeners to scientific material that is full of technical terms and has no visible connection to conditions on the ground (Conrad & Hilchey, 2011). What they learn fades quickly once the session is over.

In this programme participants took part in the field experiments themselves. They examined coal ash grains under a digital pocket microscope, compared hairy and smooth leaf surfaces, and weighed the filter papers from the dustfall jars. This hands-on, sensory involvement helped them grasp the principles of mass transfer and pollutant dispersion. Residents who had assumed that all plants absorb pollutants equally can now explain why *Casuarina equisetifolia* outperforms soft-leaved plants or palm monocultures in reducing coal dust in coastal areas.

Aerodynamics and Bio-Ecology of the Multi-Strata Green Belt

The reductions of up to 41.1% in dustfall and 37.0% in PM_{2.5} in the boundary zone are consistent with the aerodynamic theory of porous vegetation. Air masses carrying particulates from the stack and the stockpile move along horizontal pressure and wind-speed gradients (Tiway et al., 2008). When the wind meets a solid obstacle, such as a concrete wall or an overly dense monoculture with porosity below 20%, the flow is forced abruptly upward. A low-pressure zone then forms on the leeward side and produces a recirculating eddy that pulls suspended dust back down to ground level in the settlement.

The multi-strata formation designed with residents has a porosity of 40–50% and therefore acts as a permeable filter. Part of the airflow slows and loses energy as it passes through the foliage, so that coarse particles settle by gravity. At the same time, smaller particles (PM_{2.5} and PM₁₀) are trapped on leaf microstructures through inertial impaction on the trichomes of *Bambusa multiplex* and through electrostatic and chemical retention on the wrinkled cuticle of *Casuarina equisetifolia* and *Terminalia neotaliala* (Sæbø et al., 2012; Beckett et al., 2000). The three canopy layers also close the under-canopy gap, which prevents fugitive dust near the ground from slipping beneath the taller trees.

Citizen Science as a Bridge to Environmental Justice

The most substantial effect of the programme is social and political: residents' bargaining position shifted once they had their own data. Gabrys et al. (2016) describe such data as "just good enough". It may not carry the legal weight of results from an ISO 17025-accredited laboratory, yet it is scientifically valid and accurate enough to show that a pollution anomaly exists in the field.

Before the intervention, relations between the people of Karanganyar Village and the management of CFPP X were marked by friction and distrust. Complaints about coal dust in homes were frequently set aside by the company, which pointed to normal readings from its internal CEMS. Once residents had their own dustfall jars and PM_{2.5} sensors, the conversation became an evidence-based one. Participatory data from Zone 1, where dustfall

reached 22.4 ton/km²/month (224% of the limit in Government Regulation No. 22 of 2021), gave residents firm grounds on which the management of CFPP X acknowledged dust leakage during coal transfer from barges to the conveyor belt. This supports the argument of Conrad and Hilchey (2011) that citizen science is an effective means of democratising environmental oversight and of keeping conflict in industrial areas from escalating.

Limitations

Several limitations should be noted. First, the pre-experimental one-group pretest–posttest design has no separate control group, a choice made to preserve social cohesion among Ring 1 residents. Second, the vegetation was evaluated only eight weeks after planting, whereas tall shade trees need three to five years to develop a full canopy. Third, portable optical sensors are sensitive to high humidity (RH > 80%) and require periodic cross-calibration against reference instruments.

Policy Implications

The findings point to three policy directions: (1) encouraging the Ministry of Environment and Forestry to include a “community-based participatory green belt partnership” indicator in the community development criteria of the PROPER rating; (2) converting the CSR programmes of power plants into incentive-based green belt co-management schemes with resident groups; and (3) developing a mobile dashboard for residents’ air-quality reports that is linked directly to the local Environmental Agency.

CONCLUSION

The education programme on green belt structuring and participatory environmental monitoring was highly effective in raising the knowledge of residents living around CFPP X. Mean scores increased from 42.00 ± 10.8 in the pre-test to 83.10 ± 7.1 in the post-test ($p < 0.001$), with a normalized gain of 0.71 (high category).

A participatory multi-strata green belt combining tall canopy species (*Casuarina equisetifolia*, *Samanea saman*), medium canopy species (*Terminalia neotaliala*, *Swietenia macrophylla*) and understorey shrubs (*Bambusa multiplex*, *Sansevieria trifasciata*) at an aerodynamic porosity of 40–50% was successfully established along a 300 m demonstration buffer corridor.

Residents’ own monitoring data indicate that the vegetative barrier reduced dust from the plant. Dustfall fell by 41.1% in the nearest zone and PM_{2.5} concentrations by 37.0–38.3%, so that ambient air quality in the core residential zone again met the standard of Government Regulation No. 22 of 2021.

Three follow-up actions are recommended. The community should keep the “Kader Hijau Mandiri” group active in maintaining the green belt seedlings and in posting monthly dust monitoring summaries on the village notice board. The management of CFPP X should treat residents’ monitoring data as an early warning indicator for improving coal handling procedures and should extend the company green belt along the entire industrial perimeter. Future studies should take a multi-year longitudinal approach to analyse the accumulation of specific heavy metals (Hg, Pb and As) in the leaf tissue of green belt plants and to model spatial pollutant dispersion with Computational Fluid Dynamics (CFD).

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