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# From Transfer to Knowledge Co-Production: A Transdisciplinary Research Approach to Reduce Black Carbon Emissions in Metro Manila, Philippines

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**Abstract:** Air pollution, which kills an estimated 7 million people every year, is one of the greatest environmental health risks of our times. Finding solutions to this threat poses challenges to practitioners and policymakers alike. Increasing awareness on the benefits of transdisciplinary research in solution-oriented sustainable development projects has led to the establishment of the research project "A Transdisciplinary Approach to Mitigate Emissions of Black Carbon" (TAME-BC). This paper introduces the TAME-BC research setup that took place with Metro Manila, Philippines, case study. The approach integrates BC measurements with technological, socio-political, and health aspects to improve the scientific state of the art, policymaking, transport sector planning, and clinical studies related to air pollution health effects. The first pillar in the setup presents an (1) air quality assessment through aerosol measurements and instrumentation, complemented by a (2) description and assessment of the current policies, technologies, and practices of the transport sector that is responsible for pollution levels in the Philippines, as well as a (3) BC exposure and associated health impacts assessment. The fourth pillar is intercrossing, fostering (4) knowledge co-creation through stakeholder involvement across scales. We argue that this transdisciplinary approach is useful for research endeavors aiming for emission mitigation in rapidly urbanizing regions beyond Metro Manila.

**Keywords:** transdisciplinary collaboration; sustainability; sustainable development; air quality; black carbon; knowledge-transfer; innovation; measurement technology; emissions mitigation

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## 1. Introduction

It is widely acknowledged that research for sustainable development has to be context-oriented to reflect the diversity, complexity, and dynamics of the processes involved, as well as their variability between specific problem situations. Moreover, the interests and knowledge of stakeholders involved have to be considered. Sustainability research covers a wide spectrum of socio-ecological challenges, from the over-exploitation of natural resources, for example, to biodiversity loss to climate change adaptation and mitigation. In this approach, we address specific air quality challenges.

Atmospheric aerosol particles originating from the incomplete combustion of fossil fuel or biomass are proven to cause severe health issues. Particulate air pollution is currently one of the world's largest environmental health risks [1]. There is vast evidence on the negative health effects of each air pollutant, which may have synergistic effects when exposed to a mixture of ambient pollutants. Some of the most prominent health impacts of air pollution are respiratory and cardiovascular diseases, lung cancer, diabetes, and stroke [1–3]. The latest Global Burden of Disease study estimated that 4.9 million premature deaths occurred in 2017 due to exposure to air pollution [4]. Air-pollution-associated adverse health effects create large economic costs through hampered human capital formation [5] and increasing health costs [6]. Apart from negatively affecting health and the economy, absorbing aerosols, such as black carbon, contribute to rising temperatures and lead to regional climate effects [7,8]. These consequences taken together create a growing awareness for the topic of air pollution within sustainability science.

Although poor air quality remains a concern in many countries in the Global North, it poses an even bigger health risk in Asia, particularly among lower- and middle-class income population groups in Southeast Asian countries [1,9]. Compared to countries in the Global North, various low- and middle-income countries in Southeast Asia have experienced rapid urbanization, accompanied by rampant economic and industrial developments. This process comes with the trade-off of air-pollution-related complications and air quality management systems are unable to keep up with the challenges [10,11].

One striking example of rapid economic growth and rampant urbanization rates that are accompanied by high levels of air pollution is the Philippines [12]. Metro Manila, the capital region of the Philippines, is composed of 16 cities and one municipality. It is one of the biggest and most densely populated megacities in Southeast Asia, with around 13 million inhabitants [13]. An insufficient public transport system and the accelerating increase in the private vehicular fleet resulted in congested roads being filled with private cars, taxis, old buses, public utility jeepneys (PUJs), and trucks [14]. Jeepneys are a modified version of old military jeeps left behind by Japanese and U.S. soldiers. The jeepney is not only the most affordable option for getting around, it is also iconic, known as the "king of the road" and part of Filipino identity [15]. Equipped with pre-Euro standard diesel engines, PUJs are one of the responsible sources of high concentrations of combustion-generated black carbon (BC) particles, which in turn became a dominant aerosol constituent in the urban atmosphere [16]. There is limited knowledge on the characterization of air pollutants in rapidly urbanizing countries, on its health impacts to the public, as well as on measures contributing to a solution in consideration of the dynamic socio-political institutional frameworks in the country [17]. To address this knowledge gap, a transdisciplinary framework was developed called TAME-BC (i.e., Transdisciplinary Approach to Mitigate Emissions of Black Carbon). This paper introduces the TAME-BC framework in the context of Metro Manila, Philippines, and is intended to be utilized by other projects with similar goals. To do so, the paper starts by providing a brief background on one strand of sustainability research, structuring the research approach. Ensuing, the disciplinary approaches by the various institutes (pillars one to three) involved are explained before bringing them together through the integrative part of the project (pillar four).

## 2. Literature Review: Sustainability Research

Sustainability research concepts require understanding the interconnected challenges and managing unprecedented problems [18]. The broad base of various scientific approaches for sustainability research can roughly be divided into "descriptive–analytical" and "transformational" approaches [19].

"Descriptive–analytical" approaches are methodologically characterized when systems thinking and/or modeling methods are applied. These methods usually analyze sustainability problems through their past or current frameworks, correlations, and cause–effect dynamics [20–23].

A transformational approach is the second strand in the current state-of-the-art sustainability research. This framework is used for developing evidence-supported solution options for sustainability problems [19,24,25]. Working toward an evidence-based sustainability solution that meets the interests of various stakeholders requires a "transdisciplinary" research approach [26]. Solutions to environmental problems are mostly not just technical fixes or policy procedures [27,28]. Solutions for lowering pollution levels are usually as complex as the problems themselves. Therefore, sustainability research frameworks in the context of air quality management require long-term processes that involve real-world experimentation, collective learning, and continuous adaptation [19,29]. Thus, a long-term transdisciplinary approach is a key component of sustainability science when developing evidence-supported pollution mitigation options [30].

The methodological requirements necessary for transdisciplinary sustainability research are transparent, structured, and replicable sequences of steps generating knowledge as ingredients to solution finding [29]. The solutions should be based on a broad understanding of the problem (descriptive–analytical/system analysis) by considering know-how from various sets of stakeholders (scientists, decision-makers, NGOs, practitioners, etc.) [28–30]. They should further work toward a clearly stated sustainability-inspired project goal (normative/target knowledge) and outline change adaptation and transition management strategies, i.e., roadmaps for resolving the problem (instructional/transformation knowledge) [31]. Thus, transdisciplinary research needs to apply frameworks combining different types of methods and expertise to generate multidimensional applicable knowledge synergies or co-produced knowledge.

The transformational sustainability research framework, TRANSFORM, synthesizes the key features of the aforementioned frameworks [29]. TRANSFORM integrates transparent, structured, and replicable sequences of steps that generate knowledge, in which researchers

1. analyze and assess past and current states of the environmental problem,
2. trace solution-orientated project goals back to the current state of the problem, and
3. contribute to mitigating the current (pollution) problem.

Working along these steps with scientists from various disciplines and non-academic stakeholders allows for co-produced knowledge compared to knowledge produced by scientists only that is then transferred to non-academic stakeholders. The knowledge produced in such a silo is prone to overseeing certain context-specific aspects that might be of relevance to the solution.

## 3. The Metro Manila Air Pollution Case Study

The cooperation between institutes in Metro Manila and the Leibniz Institute for Tropospheric Research (TROPOS) started in 2014. An Aerosol Instrumentation and Physics Course was held at the University of the Philippines. This course led to the formation of a transnational research collaboration between TROPOS and partners from academia and NGOs in the Philippines called Researchers for Clean Air (RESCueAir). Only one year later, in 2015, the Manila Aerosol Characterization Experiment (MACE 2015) was conducted in Metro Manila to extensively characterize air pollution in three locations in the megacity.

For this purpose, an aerosol measurement container was brought from Germany to the Philippines in 2015, equipped with state-of-the-art aerosol instrumentation, to measure air pollution levels at a roadside in Quezon City, Metro Manila. The measurements focused on the physical-chemical properties of particulate pollution (for further information see Figure 1). A special focus of the measurement campaign was put on quantifying BC particles, which act as a carrier of toxic and carcinogenic components of particulate matter (PM), e.g., polycyclic aromatic hydrocarbons (PAHs) [32]. It was found that the BC levels at the roadside measurement location were up to 50 times higher than in European or North American urban areas [33]. Results also showed that the regulated levels of $PM_{10}$ from the public transport sector and particularly the BC mass concentrations are up to 70 times higher than in Europe, the USA, and other Asian countries [16]. Results from complementary mobile measurements indicated that the concentration of BC is significantly high along the roads and in areas with very high transport activities [33]. The study further concluded that jeepneys contribute to up to

94% of the overall BC emissions [16]. Based on this finding back in 2015, TAME-BC, the transdisciplinary project launched in 2019, identified jeepneys as the mode of transport under consideration.


**Figure 1.** Map of Metro Manila with the approximate locations of the intensive measurement campaigns during TAME-BC (red triangle) and MACE2015 (black cross) using state-of-the-art aerosol measurement instrumentation.

While the first data were gathered on the characterization of pollutants and marginally on health impacts (during the MACE 2015), less is known about the practices in the transport sector influencing BC emissions. Although technological solutions have been tested in many countries of the Global North, sustainable technological innovations concerning the practices in the transport sector in the tropics are yet to be tested and implemented in Metro Manila. A publication by the Blacksmith Institute and Clean Air Asia [34] has summarized the cost–benefit analysis of different technology alternatives for PUJs (compared to their pre-Euro 4 diesel engines) and recommended several action points. Those action points were discussed with government agencies, industries, and transport groups. The recommendation to adopt e-jeepneys in short, fixed routes has been implemented by some local governments, but the rest of the action points were met with financial, technical, and other implementation challenges. The government of the Philippines, having recognized the public transport sector as contributing to air pollution, among other shortcomings in the sector, has launched the Public Utility Vehicle Modernization Program (PUVMP). The program introduces a suite of measures to make public transport more sustainable [35]. One of the program components is the phasing out of conventional PUJs to have them replaced with Euro 4 compliant vehicles. As the drivers are expected to incur the costs of new units with only partial support from the government, and most PUJ drivers are part of the low-income sector, mostly without formal working contracts and their benefits, the program is facing public resistance. This discordance necessitates further efforts to understand the institutional implications of proposed solutions if inclusive and integrative sustainable actions are aimed for.

The broadened interest in developing a research project to support solution-oriented knowledge production led to the planning stage for the research project TAME-BC, which focused on a transdisciplinary approach. The novel approach that was launched in 2019 integrates the natural, health, and social sciences in addressing the perennial problem of air pollution in Metro Manila.

The transdisciplinary research setup provides a platform to gain a better understanding of the environmental impacts of BC and how to overcome the negative consequences by finding answers to the following research questions:

- What are the main sources of BC and how can we determine practices and technologies in the transport sector contributing to BC emissions?

- How can we assess the air quality regulation system, including the institutional work, the interplay of actors and institutions, and their rules and norms?
- How can we analyze and describe the potential health effects of human exposure to BC?
- How can we integrate various sets of knowledge toward air quality improvement?

The methodology presents how theoretical approaches are translated into scientific practices through an integrated transdisciplinary sustainability research approach. The following sections describe the detailed methods of the various disciplines, as well as the attempt to integrate them toward a solution orientation.

## 4. Methodology

Researching real-world challenges in the context of sustainability studies requires a co-produced knowledge process, allowing for various stakeholders from both the scientific world and the non-scientific world to be part of the research setup. In the context of air pollution in Metro Manila, previously mentioned studies found that PUJs are amongst the main polluters in the transport sector. Regarding the input into decision-making processes that impact the transport sector, participation from practitioners, such as jeepney drivers, is needed for the process of achieving sustainable solutions. Based on our literature review, the state of the art for setting up sustainability research projects is the TRANSFORM approach that we combined with the concept of "follow the innovation" (FTI). While TRANSFORM was already depicted earlier, the FTI approach allows for "joint experimentation and learning by [ … ] fostering participatory processes of testing, jointly with local stakeholders, institutional and technical innovations and adapting them to the local" [36]. Methodologically we follow the three TRANSFORM and FTI approach requirements. By combing both methodologies, we apply the following transparent, structured, and replicable sequences of three steps:

1. Current problem assessment from specific expertise areas.
2. Solution-orientated goals that reflect on the current state of the problem.
3. Combine local knowledge with specific expertise areas for the reduction of BC emission levels.

Working on air quality management in Metro Manila, the research setup described here is an innovative package of technological, socio-political, and health interventions for decision-makers to mitigate BC emissions. In detail, this is put together by a first pillar, which assesses BC pollution levels and adaptation strategies in the transport sector. The second pillar aims at understanding the institutional environment of air quality regulations, including the local and national governance structures in the Philippines. The third pillar reflects on the assessment and current state of the problem of human exposure to BC and related potential health effects. Finally, the fourth pillar analyzes the institutional workings of the air-pollution-related innovation system to effectively integrate the knowledge obtained from the findings into sustainable solutions (Figure 2). The complexity of the pollution problem "requires the constructive input from various communities of knowledge" [37], which involves a scientific inquiry approach that cuts across disciplines, synthesizes theory and methodology, and co-creates solutions. Expectations concerning the exchange of knowledge between science and policy, including knowledge coproduction [38] and local embedment, were assured by the research approach [26,27,39].

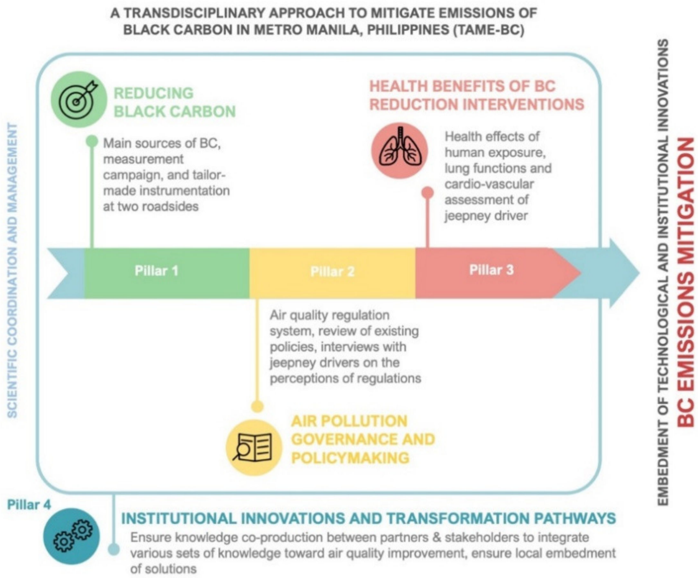


**Figure 2.** Setup of a transdisciplinary approach to mitigate emissions of black carbon (BC) in Metro Manila.

The goal of this paper then was to provide an overview of a novel transdisciplinary research framework in the context of emissions reduction that was initiated in 2019 while the implementation is ongoing. While the overall research design is a collaborative process, knowledge is also generated at a disciplinary level to then be integrated toward inclusive solution processes. The three disciplinary pillars are framed by the fourth pillar on innovation and transformation pathways, ensuring local embedment and the creation of shared knowledge. All pillars together lead to the overall aim (arrow) toward BC emission mitigation (see Figure 2).

### *4.1. Measurement Campaign: Instrumentation for Tracing Black Carbon*

This component of the sustainability research setup aims at cooperation with local partners for optimal air quality measurement campaigns with innovative technologies. The optimal technology selection for a measurement campaign should be made based on previous research [13,32] and keeping in mind the sustainability goals. If no previous research exists, it is suggested the technology selection adopts well-known world standards. When working in the Global South, it is important to apply state-of-the-art instrumentation that can be developed remotely and does not necessarily need to be produced at the measurement location, since economically less developed regions cannot afford the state of the art and there could be an issue of available expertise to do high-quality research.

In the framework of the TAME-BC campaign in 2019–2020, a measurement container was employed to determine the particulate air pollution in the Manila North Port and East Avenue (Figure 1). To ensure the gathering of high-quality measurement data, aerosol instrumentation was handled according to recommendations provided by the World Calibration Centre for Aerosol Physics (WCCAP) in the frame of the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) Programme. The sampling was done following the recommendations described by the GAW report 227 [40] to minimize the particle losses due to diffusion, impaction, and settling. Furthermore, the relative humidity was kept below 40% for the measurement, employing a Nafion®Permapure dryer [41] and by keeping the temperature in the air-conditioned measurement container at 27 °C.

The aerosol instrumentation used in TAME-BC measurement campaign includes mobility and aerodynamic particle size spectrometers (MPSS—TROPOS-type and APSS—model 3221, TSI Inc., USA, respectively), absorption photometers, such as the aethalometer and the multiple angle absorption photometer (MAAP, model 5012, Thermo Inc., Waltham, MA, USA), a volatility-tandem differential mobility analyzer (V-TDMA, TROPOS-type), an aerosol chemical speciation monitor

(ACSM, Aerodyne Research Inc., Billercia, MA, USA) to measure the aerosol particle size distribution, absorption coefficient, volatility properties, and online chemical composition of aerosol particles, respectively, and an automated weather station. Aside from the custom-made state-of-the-art measurement container, which stayed in a single location for a set time, a complimentary state-of-the-art portable aerosol backpack was developed to investigate BC exposure concentrations along the streets and in different locations that require mobility. The instrumentation inside the backpack includes an optical particle size spectrometer (OPSS, model 3330, TSI Inc., Minnesota, MN, USA) and a micro aethalometer (microAeth® AE51, MA200; AethLabs, San Francisco, CA, USA). Measurement data, such as the particle size distribution, BC mass concentration, and geospatial position, are handled by a single board computer.

Within a transdisciplinary approach, technological solutions need to be planned and applied in cooperation with local partners. Therefore, the whole measurement campaign technology selection process was a collaboration with local experts.

Theory to Measurement Practice: Appropriate Embedment in Metro Manila

The first research pillar was dedicated to the assessment of pollution levels. Considering the local conditions, it was necessary to use tailor-made instrumentation in Metro Manila that nevertheless followed world standards for high-quality data collection. The exact composition of the measurement technologies was chosen based on experiences from previous measurement campaigns in Metro Manila.

Planned measurements and investigations took place in Manila North Port and East Avenue roadsides in Quezon City (Figure 1). Air pollution sampling in East Avenue allowed for investigating the pollution at the source point. The measurements done during TAME-BC are expected to provide an accurate source apportionment and information on how the particulate air quality is influenced by different sources in Metro Manila [42]. Such systematic pollution characterization gives the necessary additional insight into the health risks of exposed populations.

The establishment of long-term air-pollution-monitoring sites is vital for tracking the changes in BC concentrations. Long-term monitoring ensures tracing solution-orientated project goals back to the current state of the problem. Assessment and tracking project realization was the aim of the air quality measurement practice within this project. The long-term air-pollution-monitoring site was suggested to be located at the Manila Observatory (MO), where MACE2015 previously stationed aerosol instrumentation as a representative of urban background pollution level. Such a continuous scientific monitoring component is important because it can provide high-quality and long-term data to validate the effectiveness of technological, socio-political, and health innovations and transformations in reducing the emissions of BC in the course of this project and beyond.

The measurement and investigation stages executed in Metro Manila, Philippines, relied on the literature review and on the methods that were proven to provide comprehensive information on the pollution properties in TROPOS's previous studies in Metro Manila involving container measurements (e.g., estimating the emission factors) [16,43] and in mobile measurements studies [33]. Although the air pollution data is not presented in this manuscript, the goal of pillar one is to perform a thorough air quality assessment. The Metro Manila case study example that focused on BC emissions aimed at a scientific collaboration with the local science institutes by doing container measurements as part of pillar one. Measurements through the TROPOS Aerosol container were performed in the port from 19 December 2019 to 25 January 2020. Measurements in East Avenue right outside the Quezon City Hall ran from 30 January 2020 to the end of 25 February 2020. Compared to the port, higher BC concentrations were observed in East Avenue, which was heavily influenced by local heavy vehicle traffic emissions. Such a setup involving placing a measurement container in two various places provides the local transport planning authorities and policymakers with quality data for better decision-making. Container measurements provide the most accurate data on air pollution (compared to mobile sensors), and for the specific Metro Manila case study, the BC values in 2019 were observed to be higher than what was measured by Alas et al. in 2015 [33] in Taft and Katipunan Avenue.

This component of the setup focuses on applying the TROPOS measurement container and is a valuable scientific addition to the TAME-BC, as it serves as a quality assurance for all measurements made within the project. Policy assessment, coordination, and health awareness pillars draw their conclusions based on the aerosol characterization done in this pillar. Therefore, air pollution measurements should be covered in the first pillar to serve as a starting point for further actions.

### *4.2. Air Quality Management and Policy Implications*

Investigating the institutional settings of past and current states of air pollution challenges by applying a case study approach in Metro Manila represents the second pillar. The problem of air pollution was already assessed and recognized by the government of the Philippines in the 1990s. Even though air pollution measurements were not as detailed back then as under the current project, it led to the issuance of the Philippine Clean Air Act in 1999. The Department of Transportation (DoTr) recently initiated the already mentioned PUVMP, mainly aiming to modernize the public transport fleet toward Euro 4-compliant engines for all public utility vehicles, where the obvious targets among those are also the unique jeepneys. Such a decision created division: Some of the affected groups oppose the modernization program arguing that it threatens transport cooperatives and single-unit jeepney owners. The government, however, remains committed to the phase-out of vehicles using older engines to ensure safety and decrease pollution, despite strong resistance. Lack of scientific knowledge in implementing environmentally and socially sustainable solutions may result in a failure of the PUVMP, which will affect the livelihoods of many people.

To gain a deeper understanding of the institutional environment surrounding air quality management in the Philippines, the two-fold approach that is taken must be highlighted. As suggested by the selected TRANSFORM methodology, foresight and back-casting methods adopted to FTI were applied. On the one side, a thorough content analysis of the regulations in place and how they evolved was conducted. On the other side, discrepancies between the de jure and de facto regulations can only be unraveled by understanding how those regulations are embedded in a wider institutional context on the local level. This means that interviews with those affected by the regulations are conducted.

#### Theory to Policymaking Practice: Appropriate Embedment in Metro Manila

While the political and public awareness toward air pollution-related problems in Metro Manila is increasing, this fosters de jure governance responses by state institutions and de facto mechanisms of the public down to the individual behavior level. However, fairly little is known about current management mechanisms that deal with increasing emission levels [17].

The second goal of TAME-BC, therefore, was to investigate and systematically map the dynamically evolving local institutional environment. It includes the evaluation of policies, rules, norms, and values that determine the current state of air quality in Metro Manila. This supports examining knowledge flows on air pollution and its mitigation management, based on local case studies.

In assessing the de jure governance responses to the decreasing air quality in the Philippines, a systematic mapping of governmental regulations served as the first step of the investigation toward air-quality-management-related policies. Starting with an analysis of the Clean Air Act from 1999, relevant ensuing regulations were investigated as well. This was done through the investigation of the national governmental authorities' homepages. The main contributions were from the Department of Environment and Natural Resources (DENR) and the DoTr. The most relevant documents were listed and analyzed through a qualitative content analysis using ATLAS.ti (version 8.4.16, Scientific Software Development GmbH, Berlin, Germany). The regulations on the PUVMP were furthermore considered, even though the program was not implemented in the context of air quality management in the first place [14]. Nevertheless, as the program aims to replace the old diesel engines with at least Euro 4 standard engines, it was of importance to the overall analysis. Based on the review of air quality management regulations, qualitative semi-structured interview guidelines were developed. The interviews were conducted to study the local level response to policies. Open-ended questions avoided collecting biased pre-formulated answers [44]. Jeepneys are over-proportionately contributing to air pollution. The drivers are over-proportionately exposed to pollutants. Therefore, the target group of the interviews was the jeepney drivers. Various jeepney driver associations serve different routes within Metro Manila. As the jeepney drivers themselves are a very heterogeneous group, they have different perspectives on air pollution, as well as on the modernization program. The different jeepney drivers often position themselves toward the modernization program along the line of opposing the project toward more moderate positions. Within the frame of the TAME-BC project, we interviewed three jeepney driver associations, representing different positions toward the modernization program. One group interviewed rejects the modernization program. A second group interviewed had a moderate stance, while the third group interviewed already participated in the modernization program. This variety allowed for a comprehensive information collection framework. The groups were further selected in regard to the area they worked in. One group interviewed passed the TROPOS container on their route. An additional overlap was created as jeepney drivers were also investigated by the mobile backpack measurement team.

The interviews were conducted with one driver at a time while being on the moving jeepney during usual business hours. A total of approximately 10 interviews per group was conducted ($n$ = 30), where an interview lasted for an hour on average. This also allowed for participatory observation during the time on the jeepneys. Additional interviews were conducted with government representatives from the DENR, the DoTr, a local government unit, and NGOs working in the field of air quality. All interviews, but especially the ones with jeepney drivers, were conducted together with a local research assistant. The research assistant guaranteed ease of the interview situation, mainly by allowing the interview partner to interview in her or his preferred local language. Interviews were recorded and transcribed when permission was granted. The researchers also took notes during the interviews. After each interview, the notes were typed up and discussed among the research team.

Combining interview results with the mobile and stationary measurements can be used for a comprehensive analysis that serves the goals of pillar two. By having identified the exact pollution levels on various routes that were complementary to interviews with the jeepney drivers, the de jure and de facto policy assessment implications of pillar three have a strong basis for producing better local transport sector guidelines.

### *4.3. Awareness Building: Health Effects Estimation*

The third pillar of TAME-BC was conducted in close cooperation with local hospitals for building health awareness with regard to air pollution problems. The health component of the project aims to increase knowledge of adverse health effects caused by ambient air pollution, as suggested in the following paragraph.

The exposure to BC has to be measured ideally for the main polluters and for those who are the most affected. Measurements of BC inside jeepneys was conducted by using portable instruments (backpack measurements) used at different locations during different days and times to allow for a more precise picture of the BC exposure levels for the drivers. Ideally, such measurements are done at various times of the day, weeks, and months such that comparisons can be presented. Further, the lifestyle and health conditions of the main polluters and those who are most affected should be assessed using the Burden of Obstructive Lung Disease (BOLD) study questionnaire. The BOLD study is an already existing cross-sectional survey that assesses the prevalence and burden of chronic obstructive pulmonary diseases (COPDs) in the Philippines, which developed a validated questionnaire. The lung functions of the main polluters and those who are most affected should be examined, ideally using pre- and post-bronchodilator spirometry measurements. Additionally, a cardiovascular assessment should be performed. This includes an electrocardiogram and blood pressure measurements. Lastly, the association between BC and health outcomes can therefore be analyzed using linear or logistic regression models depending on the classes of the outcome variables (e.g., continuous or binary variables). A set of previously selected covariates are recommended to be included to control for their potential confounding effects, such as age, sex, and socioeconomic and lifestyle variables.

#### 4.3.1. Theory to Awareness Building Practice: Appropriate Embedment in Metro Manila

Exposure to pollution has several negative associated health effects, as described above. The theory described in the section above was applied in Metro Manila for the goal of BC emissions reduction via awareness building.

(1) The exposure of BC in jeepney drivers was quantified using personal measurements collected with mobile instrumentation inside the moving jeepney. TROPOS backpacks with portable instruments (consisting of (a) an AE51 Aethalometer, (b) an optical particle sizer, (c) Crowdsense, and (d) a personal air sampling monitor) was used for exposure measurements from January to February 2020 in two different locations. This approach provided an opportunity to compare the spatial distribution of BC between two different environments in Quezon City. Furthermore, the weekdays versus the weekend BC concentration levels were compared. A portable BC instrument in a backpack was used in two jeepney routes, with different microenvironments (Arayat, Cubao-Quezon City Hall (QCH), and UP Ikot (University of the Philippines, *ikot*= to go in circles), with sampling done during the morning, midday, and afternoon.

(2) The lifestyle and health conditions of the jeepney drivers were assessed using the BOLD study questionnaire. The BOLD study (https://www.boldstudy.org/) is an already existing cross-sectional survey that assesses the prevalence and burden of COPDs in the Philippines, which developed a validated questionnaire.

(3) The lung function of jeepney drivers (the same cohort interviewed under pillar two) was examined in the Lung Center of the Philippines (LCP) using pre- and post-bronchodilator spirometry measurements. Additionally, a cardiovascular assessment was performed, which included an electrocardiogram and blood pressure measurement.

(4) The association between BC and health outcomes was assessed using linear or logistic regression models depending on the classes of outcome variables (e.g., continuous or binary variables). A set of previously selected covariates was included to control for their potential confounding effects, such as age, sex, and socioeconomic and lifestyle variables.

We foresee that such data obtained will be vital to health outcome studies. Such studies are being conducted at the LCP to assess the health effects of BC, as BC particulates are known carriers of toxic substances. The data collected in pillar three will also be useful as much-needed evidence to aid policymaking regarding measures to address air pollution, especially now that the public is more conscious of taking care of their respiratory health.

##### BOLD Questionnaire Investigation

Between January 2020 and March 2020, approximately 100 jeepney drivers were investigated by trained personnel using the BOLD questionnaire at the LCP. The BOLD questionnaire collects information on occupations, indoor/outdoor environmental exposures, socioeconomic status (e.g., income), health conditions (e.g., cardiorespiratory symptoms, and sleeping and breathing disturbance), lifestyles (e.g., smoking), physical activities, and other issues.

##### Lung Function and Cardiovascular Measurements

Between January 2020 and March 2020, 100 jeepney drivers were invited to the LCP where measurements on lung and cardiovascular functions took place. Lung functions were measured using the spirometer EasyOne Air (Medizintechnik AG, Zurich, Switzerland) by trained personnel in line with the American Thoracic Society/European Respiratory Society [45]. Briefly, a questionnaire was performed before the measurements to exclude drivers with pre-existing contraindications. For each participant, at least three but not more than eight trials were performed under the guidance of a professional to obtain the optimal spirometric values. Subsequently, each participant inhaled a bronchodilator (e.g., salbutamol) using a metered-dose inhaler. The lung functions were re-measured 15 min later to get the post-bronchodilator measurements. For participants with successful spirometric measurements, the electrocardiogram and blood pressure were measured according to the manufacturers' instructions.

Although the exact result of pillar three will be discussed in a complementary manuscript, by doing the spatiotemporal analysis, it was possible to show that the mean and median BC concentrations varied between different routes for different times of the day. The pillar three actions help to identify air pollution levels in various locations. Namely, it was recorded that for the Arayat, Cubao-QCH route, the median measurement was ≈53.5 $\mu g\ m^{-3}$, while the mean was 68.4 $\mu g\ m^{-3}$. Additionally, the preliminary results showed that higher values were measured in the morning, before 10 a.m. Such results were obtained by conducting a total of forty runs of around 13 km jeepney-travel distance, which lasted 1–2 h per ride. Thirteen drivers participated in the measurements. Additionally, spatial analysis plots showed that equivalent black carbon (eBC) concentrations were higher along QMC and East Avenue, which had higher traffic volume compared to the rest of the route, and were at a minimum in the Arayat market area. In comparison to the UP IKOT route, where 42 runs were accomplished around the 5 km loop (≈25 min per loop), with around ten participating drivers, the median value recorded was 31.0 $\mu g\ m^{-3}$. The mean value there was 41.5 $\mu g\ m^{-3}$ for this specific route. Higher values were observed in the afternoon after 3 p.m. Furthermore, several pollution hotspots could be identified along the C.P. Garcia Avenue, which is a busy thoroughfare that experiences higher traffic volumes compared to inside the UP campus when using the mobile sensors on moving jeepneys. The two routes experience different traffic and environmental characteristics, which also has different implications for regular drivers and commuters of the routes. Such variations provide important input for clinical studies and health-related local research.

### *4.4. Coordination: Innovation Embedment via Stakeholder Engagement*

The fourth pillar of the project cuts across disciplines and integrates non-academic partners into the research project for tracing solution-orientated project goals back to the current state of the problem. As the project focuses on the innovation potential and capacity development concerning the mitigation of BC emissions through an assessment of regulatory measures, involving stakeholders from the administration, economy, and science sectors, as well as practitioners from the transport sector, is crucial.

Involving a wide spectrum of stakeholders can be achieved through a series of participatory workshops that consciously avoid disciplinary expert jargon. Local stakeholder involvement provides empirical insight into air-quality-specific innovation opportunities. The project aims at developing recommendations for the further development of air-quality-specific capacities. This can be achieved by bringing together local knowledge of practitioners and other stakeholders involved with experiences of adaptation and innovation potential toward an improved air quality situation.

The transdisciplinary FTI approach is followed using a manual by [46], where the local coordination is in charge of ensuring the success of the fourth pillar. The emphasis in this context is put on the participatory process of identifying, testing, and adapting innovations with stakeholders from different sectors. By following the steps of the FTI approach and applying the TRANSFORM approach, the fourth pillar of the TAME-BC project focuses on systematic and strategic stakeholder engagement toward collective agreement to collaborate and co-create solutions [46] and on testing transition and intervention strategies [29].

#### 4.4.1. Theory to Local Coordination Practice: Appropriate Embedment in Metro Manila

To root the technological, political, and health awareness practices into the local environment, a local NGO served as the coordinator on the ground. Building on its already established network and the trust of stakeholders in this network allowed for promising cooperation within the expanding network.

Appropriate embedment in Metro Manila started with cooperation among policy- and decision-makers to strengthen air quality management systems and identify spaces within institutional frameworks for innovation development and adaptation in air quality improvement, including BC mitigation. The goals were achieved by a series of capacity development workshops for innovation-based change adaptation.

Building the Stakeholder Network as a Dialogue Platform for Collective Learning and Change Adaptation

According to Lang et al. [37], building a collaborative research team is the first step in conducting a transdisciplinary research project. This was followed by the creation of a joint understanding of the real-world problem the consortium had broadly identified. For TAME-BC, this meant developing a communication strategy and approaches that matched the local context and reflected the priorities of the partners and stakeholders. Building on the NGO's existing network of contacts, key stakeholders, in addition to those already engaged by the project, were identified and mapped. With the help of other partners, institutional and operational links between government and non-government agencies were specified, together with the most efficient and strategic mechanisms of engaging them. A communication platform was established through internal and external directories, for ease of communication with all groups involved. Ensuring clear communication systems was necessary for a smooth transition for the identification of change adaptation potential once the findings from the study are consolidated.

Identifying a Methodological Approach to Combine Collective Reflection, Learning, and Air-Quality-Related Innovation Development

As the list of stakeholders ranges from scientists to jeepney driver association representatives to NGOs and local government representatives, it is a prerequisite to find a way to include all members of the team in the dialogues. Further following Lang et al. [37], a methodological framework for collaborative knowledge production was of crucial importance within the process of moving from knowledge transfer toward the co-creation of knowledge. For the identified stakeholders, regular group meetings are required. In parallel, discussions between various groups were facilitated and the results were shared within the wider stakeholder group. Workshops were conducted to encourage the transdisciplinary approach and further stimulate the development of air-quality-related innovations. Resources, such as publications, reports, and relevant news, were continuously disseminated through the communication platform established as a first task. For the stakeholders not directly involved in the interviews and workshops, leaflets were developed. The figure below (Figure 3) presents one example. At the beginning of the project, after agreeing on a shared problem definition, a leaflet summarizing the main research questions was prepared. It reflects on the four pillars and the overall goal of the project. This was presented in a graph and in simple language (in Tagalog, the local language in Luzon, the research area) to allow for ease of interaction with the information.

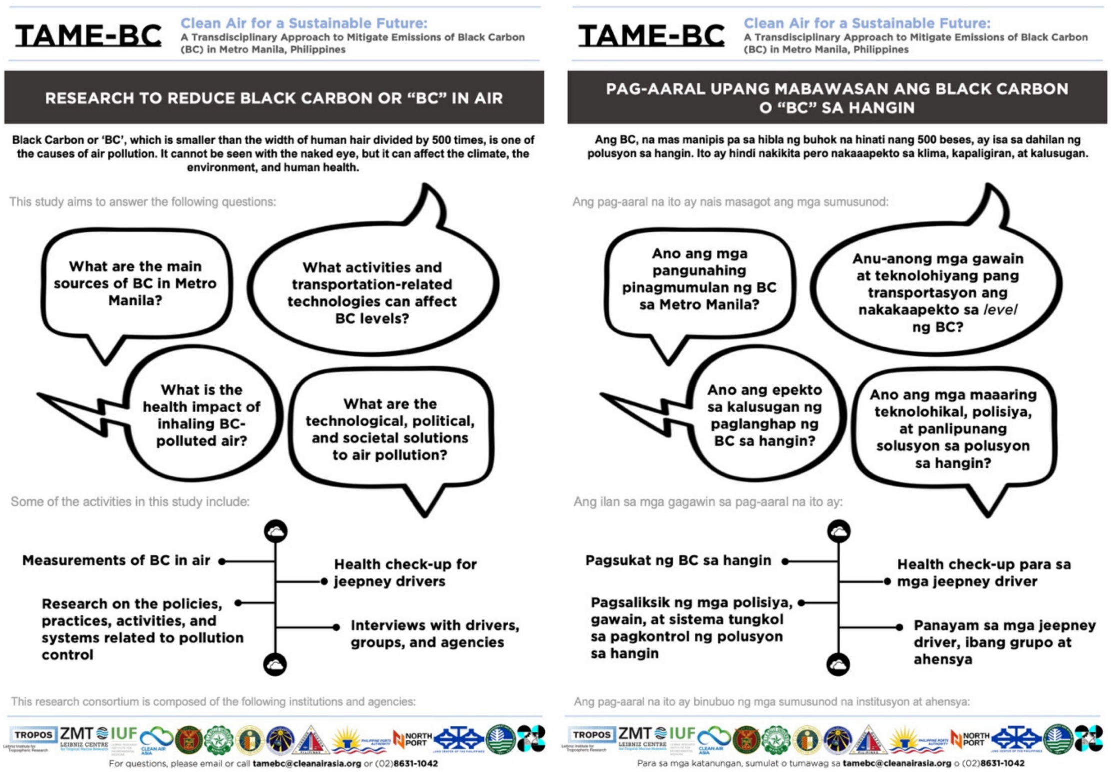


**Figure 3.** Leaflet in simple terms in the local language (right panel) to involve all stakeholders in the process.

Localizing a Concept for Innovation-Based Change Adaptation and Transition Management

Input from the technology, policy, and health effects practices was consolidated. Methodological needs and gaps from that input were identified. The input was improved for the development of innovation-based change adaptation and management. A research implementation roadmap was created that identified appropriate partners, most central project activities, and timelines. Throughout the process, there was a consistent reporting and documentation process in place to support the shared learning processes.

Developing Reports on Transdisciplinary Workshops and Process Documentation

Workshop and meeting reports, project reports, and other outputs must be continuously consolidated and shared with concerned partners and stakeholders. In all related documentation and reporting activities of the project, it was ensured that inputs from all stakeholders, especially PUJ drivers and government agencies, were valued. The outcomes of the various steps of the innovation embedment methodology were presented as a knowledge brief, policy assessment report, and a report on possible technological innovations. A draft action team and project roadmap were jointly developed, paving the way for innovation development.

## 5. Discussions and Limitations

For solving complex real-world sustainability problems, as outlined above, it is vital to bring together a broad range of researchers, practitioners, and stakeholders with a shared vision and goal. Collaborative research endeavors are challenging since this requires cooperation across disciplines and scales; therefore, the effectiveness of such research can be hard to measure in the short-term. At the same time, we regard the network that the project was able to build so far and its communication strategy as a major contribution toward a potential solution. Bringing stakeholders from the physical sciences, the social sciences, and the health sciences, as well as non-government and government representatives and practitioners, in our case, the jeepneys driver association representatives, together to discuss air pollution is a novelty in itself. To then follow a systemic approach in which the problem was collectively defined and agreement on the search and development for potential solutions was achieved is the basis for further collaboration. The Department of Transportation, a major stakeholder, agreed to work closely with the team and to become a part of it. In Figure 4 below, the TRANSFORM and FTI approaches applied for TAME-BC are displayed. Assessment and analysis (step one of the TRANSFORM approach's requirements) of the air pollution levels (Port, Quezon City (QC), and background BC levels) is the work conducted in pillar one. In pillar two, by incorporating de jure governance responses by state institutions and de facto mechanisms of the public, we study past and current states of the environmental problem (step two of TRANSFORM: provide solution-orientated goals that reflect the current state of the problem). Pillars three and four contribute to the mitigation of the air pollution problem by building awareness among the PUJs and by involving important local stakeholder networks. Pillar four is crucial for local embedment. The fourth pillar ensures that solution-oriented results from all other pillars are locally adopted and embedded in Metro Manila (step three of TRANSFORM: contribute to mitigating the current (pollution) problem).

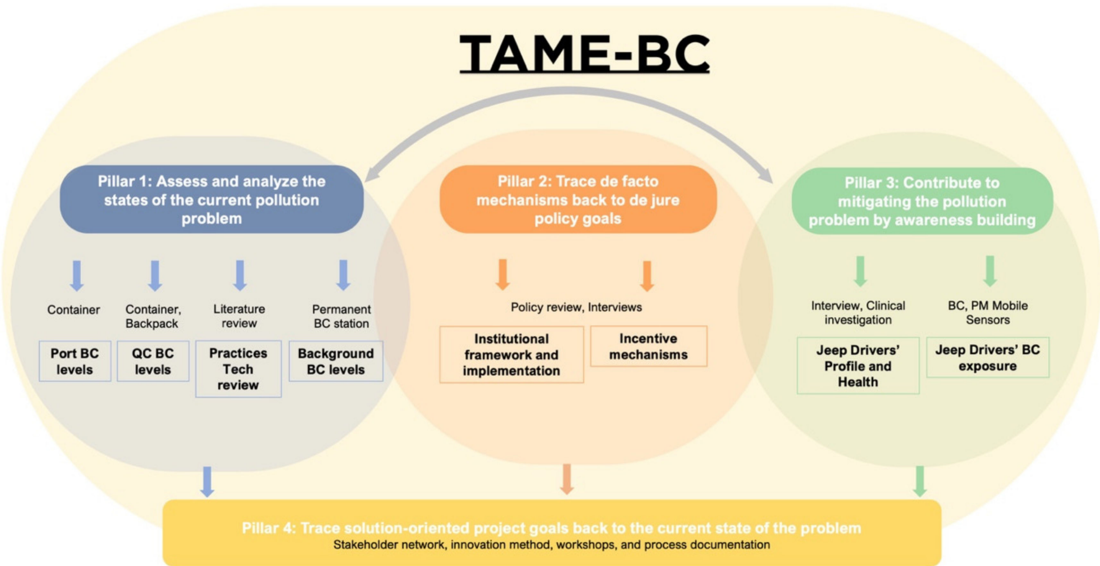


**Figure 4.** The "follow the innovation"(FTI) and TRANSFORM methodology steps displayed using the four pillars of the TAME-BC set-up.

For solving sustainability problems, tailor-made approaches are needed. Since every scientific attempt has a different method for tackling sustainability problems, it is hard to compare the methodologies. The state of the art on transdisciplinary research processes for more sustainability is still in the early stages. Although there is a growing number of publications on the topic, it is not possible to compare the research setup in this manuscript with a similar scientific approach in the past. TRANSFORM and FTI provide a scientific basis for conducting air pollution mitigation research. Nevertheless, due to changing local conditions and different sustainability goals, no comparable scientific approach has been taken before, according to the knowledge of the authors. If a similar scientific transdisciplinary approach emerges in the future for addressing sustainability problems, it is recommended to compare the results and effectiveness of the practices applied.

## 6. Summary

The procedural method presented is a novel approach in the context of sustainability research without presenting measurement or analysis results for each pillar. The four pillars bring together researchers from the environmental, social, and health sciences for assessing air quality challenges and solution-oriented goal setting. The setup includes stakeholders from science, non-governmental organizations, and government agencies to allow for local innovation development.

The methodology applied in TAME-BC follows the TRANSFORM and FTI approaches. This transdisciplinary approach consists of (1) the measurement of air pollutants, (2) the study of policy implications for air quality management, (3) exposure-related health effects estimations, and (4) local coordination and knowledge production. The TAME-BC approach provides a systematic integrative approach that aims at BC reduction. This setup starts by jointly defining the existing pollution challenges (complex problem constellation) and investigating solution-orientated goals (plausible future constellations) that reflect the current state of the problem (sustainable constellation) by involving various stakeholders (transition strategies).

Applying this approach to air quality challenges in Metro Manila highlights (1) the importance of novel and custom-built measurement technologies for scientific air quality measurement campaigns; (2) the necessity to involve local-level stakeholders to establish a response to policies aiming at BC emissions reduction processes, as well as the prerequisite of innovation roadmaps via attractive legal frameworks; (3) awareness-building processes among healthcare systems and local infrastructures. Finally, the paper emphasizes (4) the need to involve a broad set of stakeholders, including the identification of a shared language and shared goals. Instead of presenting results for all four pillars, this paper suggested that information collected via such a setup can be used for improvements in transport sector planning, policymaking, clinical studies, and state-of-the-art scientific studies. (see Figure 5).

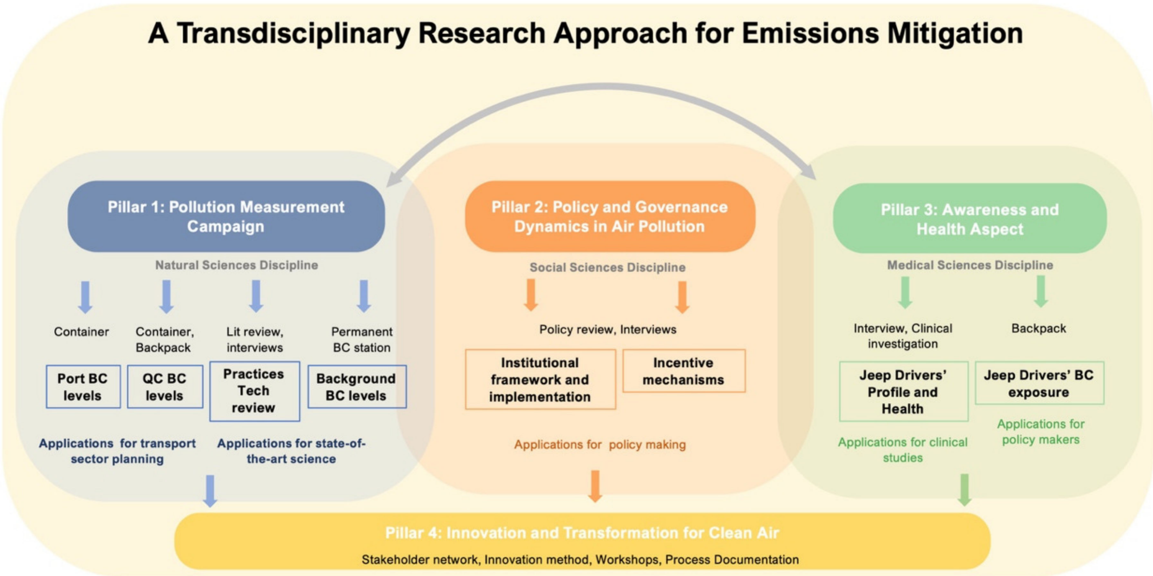


**Figure 5.** Visualization of a novel approach for sustainability research in the context of air quality management.

Bringing the four pillars together by following the FTI and TRANSFORM approaches in Metro Manila proved that custom-built technological solutions are necessary for high-quality data collection regarding air pollutants. Additionally, the high-quality data needs to be translated into the local context by analyzing de jure governance responses by state institutions and de facto mechanisms of the public down to the individual behavior of jeepney drivers. Third, awareness-building via knowledge on health effects needs to also be built with local stakeholders to guarantee sustainable change adaptation. Finally, these three scientific steps for BC emissions reduction need to be translated well into local networks, and therefore, a local partner is essential for innovation embedment via stakeholder engagement. These steps ensure a successful transdisciplinary approach for improved air quality and sustainable change-making. Such a setup has an impact on the local scientific state of the art (pillar one) through scientific emissions assessment, together with local partners. Applying the policy fore-, and back-casting assessment and awareness building pillars (pillars two and three) is also done. The fourth pillar has the potential to combine the knowledge produced toward the development of pollution mitigation.

This transdisciplinary approach aiming at reducing emissions in Metro Manila combined the FTI and TRANSFORM approaches and contributes to the sustainability science by developing and validating a novel approach for sustainability research in the context of air quality management.

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## Abbreviations

| | |
|---|---|
| BC: | Black carbon |
| NOx: | Nitrogen oxides |
| O3: | Ozone |
| CO: | Carbon monoxide |
| Pb: | Lead |
| PAHs: | Polycyclic aromatic hydrocarbons |
| TAME-BC: | Clean Air for a Sustainable Future: A Transdisciplinary Approach to Mitigate Emissions of Black Carbon in Metro Manila, Philippines |
| ZMT: | Leibniz Centre for Tropical Marine Research |
| IUF: | Leibniz Institute for Environmental Medicine |
| DIE: | Deutsches Institut für Entwicklungspolitik/ German Development Institute |
| TROPOS: | Leibniz Institute for Tropospheric Research |
| BMBF: | German Ministry for Education and Research |
| DOTr: | Department of Transportation |
| PUVMP: | Public Utility Vehicle Modernization Program |
| PUV: | Public Utility Vehicle |
| PUJ: | Public Utility Jeepney |
| DENR: | Department of Environment and Natural Resources |
| BC: | Black carbon |
| NOx: | Nitrogen oxides |
| O3: | Ozone |
| CO: | Carbon monoxide |
| Pb: | Lead |
| PAHs: | Polycyclic aromatic hydrocarbons |
| QC: | Quezon City |
| TAME-BC: | Clean Air for a Sustainable Future: A Transdisciplinary Approach to Mitigate Emissions of Black Carbon in Metro Manila, Philippines |
| ZMT: | Leibniz Centre for Tropical Marine Research |
| IUF: | Leibniz Institute for Environmental Medicine |
| DIE: | Deutsches Institut für Entwicklungspolitik/German Development Institute |

TROPOS: Leibniz Institute for Tropospheric Research
BMBF: German Ministry for Education and Research
DOTr: Department of Transportation
PUVMP: Public Utility Vehicle Modernization Program
PUV: Public Utility Vehicle
PUJ: Public Utility Jeepney
DENR: Department of Environment and Natural Resources

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