Air quality from pictures: benchmarking and assessment of image-based methods for Particulate Matter estimation (AQpictures)

Technical Report

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Lead WGs

IV/7: Intelligent Systems in Sensor Web and IoT

Contributing WGs

III/8: Remote Sensing for Agricultural and Natural Ecosystems

Executive summary

Air quality monitoring remains a critical challenge for public health and environmental protection, particularly in urban areas where air pollution levels frequently exceed recommended thresholds. While regulatory-grade monitoring networks provide accurate and standard-compliant measurements, their limited spatial coverage and high operational costs motivate the exploration of complementary monitoring approaches. In this context, recent research has demonstrated that visual information extracted from outdoor images and fixed webcams can be exploited to support the estimation of harmful airborne pollutants such as the Particulate Matter (PM). The AQpictures project was conceived to systematically assess and benchmark image-based PM estimation methods reported in the scientific literature, with emphasis on reproducibility. To this end, the project combined a state-of-the-art review, the implementation and evaluation of representative methods, and the development of an open scientific toolkit supporting method replication and extension. Selected methods were evaluated using harmonised data preprocessing and validation workflows and assessed against authoritative ground-based PM observations, using as a case study the metropolitan area of Milan (Italy). The project delivered several outcomes, including (i) a literature review paper, (ii) a technical note documenting data preparation procedures, model implementations, and accuracy assessment protocols, and (iii) an open GitHub repository hosting code, sample datasets, and technical documentation. Dissemination activities included a workshop and a scientific contribution accepted for publication in the *ISPRS Archives* for the XXV ISPRS Congress.

1 Project activities

Project activities were organised into three main work packages, in line with the approved project plan (see Figure 1), and were carried out between January and December 2025. These packages addressed, respectively: state-of-the-art review, benchmarking, and data preparation; development and implementation of image-based PM estimation methods; and dissemination and outreach activities. The following sections provide a high-level overview of the activities conducted within each phase, while detailed scientific results and methodological aspects are documented in technical papers currently submitted for publication.

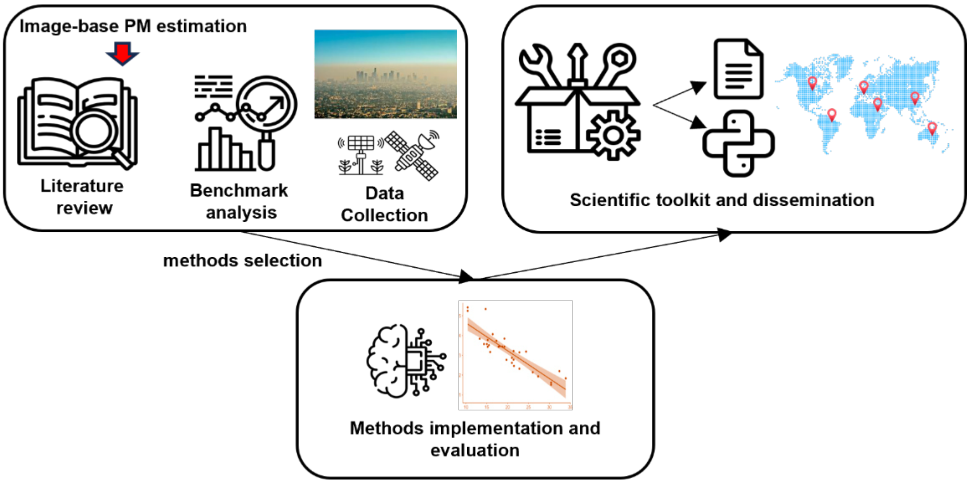

Figure 1: The AQpictures project workflow

State-of-the-art, benchmarking, and data preparation

In the initial part of the project, activities focused on consolidating the scientific background and preparing the datasets required for methods implementation and evaluation.

A scoping review of the scientific literature on image-based PM estimation methods was conducted, with particular attention to approaches compatible with open and reproducible implementation. In total, 46 peer-reviewed articles published between 2014 and 2024 were analysed. The identified methods were classified according to their input data requirements, algorithmic principles, and reported performance. The outcomes of this review provided an overview of the principal methodological approaches proposed within the scientific community, together with the types of input data, preprocessing procedures, and evaluation strategies most commonly employed. The analysis reveals a wide diversity of image-based methods for $PM_{2.5}$ estimation, which can be broadly classified into four methodological categories: (i) physics-based models grounded in principles of atmospheric optics; (ii) machine-learning approaches leveraging image-derived features such as colour ratios, contrast measures, haze indices, and texture descriptors; (iii) deep-learning models based on convolutional or recurrent neural network architectures; and (iv) hybrid approaches integrating physical priors, image-extracted features, and ancillary spatio-temporal variables, including meteorological information. Across these methodological categories, deep-learning approaches generally exhibit the highest predictive performance, although in many cases their accuracy remains below the levels required for authoritative air quality monitoring. The review further indicates that the majority of existing studies are geographically constrained and often rely on limited datasets, with data and code availability remaining a major barrier to reproducibility and systematic benchmarking. Only a small subset of studies release both datasets and source code. These limitations are frequently attributable to licensing, privacy, or data ownership constraints, particularly in the case of surveillance and fixed-camera imagery. A complete and structured synthesis of the review results has been consolidated into a review paper which is currently under consideration for publication in a scientific journal.

In parallel to the review, data collection and preprocessing activities were carried out using the city of Milan (Italy) as a case study. Outdoor images were collected from a publicly accessible fixed webcam and paired with ground-based PM measurements from authoritative monitoring stations. A site-selection procedure was applied to identify webcam–station pairs with suitable spatial and temporal overlap. The resulting datasets were harmonised and processed into analysis-ready formats, providing inputs for the subsequent development and testing activities.

Development

In the second phase of the project, activities focused on the implementation and evaluation of selected image-based PM estimation methods on the Milan case study spanning three methodological families: physics-based, machine-learning, and deep-learning approaches. Methods were selected based on the state-of-the-art review and implemented through Python scripting using open-source libraries. The impelmentation workflow included standardised image preprocessing and segmentation, image features extraction, and temporal synchronisation with ground-based $PM_{2.5}$ observations. Image-derived features were complemented with meteorological and reanalysis variables to account for atmospheric conditions affecting visibility and aerosol dispersion at the each specific acquistion time. Physics-based modelling relied on entropy-derived visibility indicators (see Figure 2), while learning-based approaches used colour and brightness features for regression. Harmonised validation strategies and regression-based accuracy metrics were applied consistently across methods.

Figure 2: Comparison of saturation channel images: the left panel shows a clean-air scene, whereas the right panel depicts a polluted scene associated with high $PM_{2.5}$ concentration.

The physics-based model showed limited sensitivity to pollution variability and overall weak predictive capability. The deep-learning model based on a Multilayer Perceptron exhibited unstable training behaviour and poor generalisation to testing data. Among the implemented approaches, the machine-learning model based on Classification and Regression Trees (CART) architecture achieved the best overall performance, yielding strong in-sample accuracy ($R^2 > 0.94$), although its predictive accuracy decreased substantially on independent test data, indicating residual generalisation issues (see Figure 3). The development phase highlighted limitations in model performance and indicated the need for improved handling of illumination regimes, stronger control of overfitting, and broader training datasets. Full methodological details and evaluation results have been consolidated into a technical note, which serves as the main scientific reference for this phase. The revised and extended content of this technical note has been included in a paper accepted for publication in the *ISPRS Archives*.

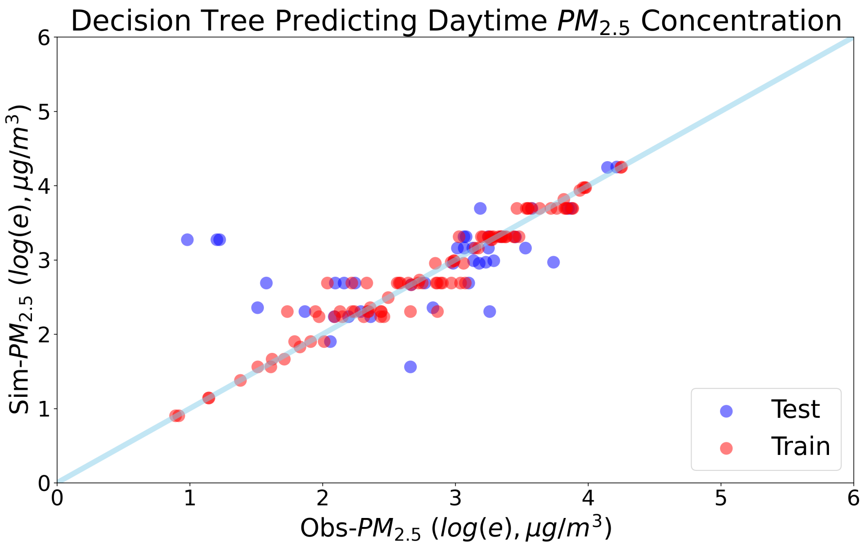

Figure 3: Daytime CART model performance for a sample run on Milan data: observed vs. predicted $PM_{2.5}$ in log-space for training and testing samples.

Dissemination and outreach

In the final part of the project, activities focused on dissemination of project materials and engagement with the scientific community. The scientific toolkit developed within the project—including code, sample datasets, and documentation—was released through an open GitHub repository (see Figure 4) to promote transparency, reuse, and reproducibility. The repository also serves as the central access point for all publicly available project resources (https://github.com/gisgeolab/aqpictures).

In addition, a dissemination workshop was organised in a hybrid format to introduce the project objectives, methodology, and preliminary outcomes. The workshop was delivered within the PI-format class session and streamed online to enable broader participation (with 35+ participants reached). Presentation materials and supporting resources used during the workshop were included in the project open repository. Finally, as part of the scientific dissemination activities envisaged by the project, a contribution to the XXV ISPRS Congress was prepared, submitted, and accepted for publication in the *ISPRS Archives*, thereby supporting formal dissemination of the project outcomes within the ISPRS scientific community.

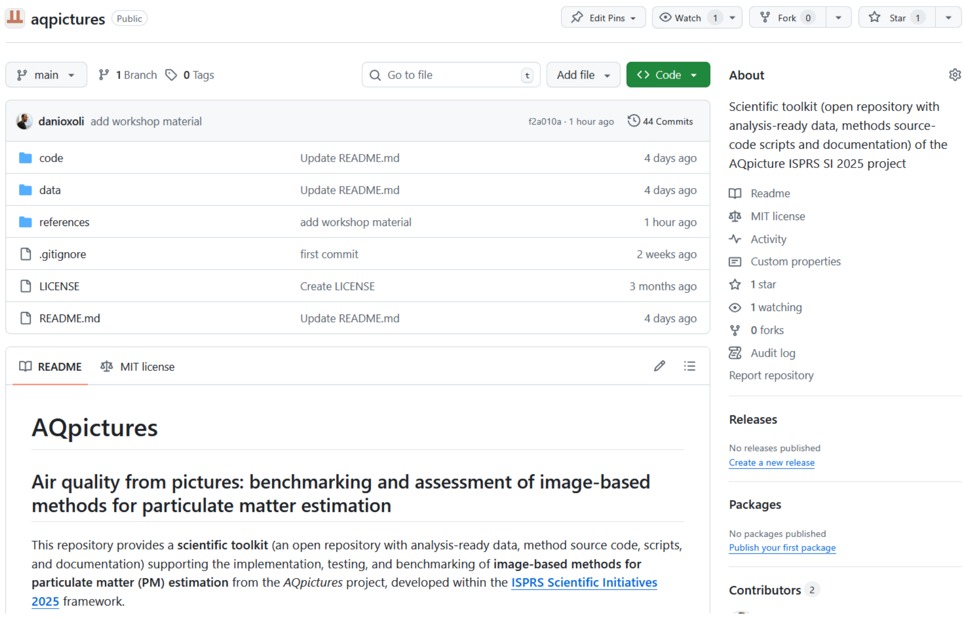

Figure 4: The AQpictures GitHub repository landing page.

2 Project outcomes

The AQpictures project delivered a set of scientific, technical, and dissemination outcomes aligned with the objectives defined in the approved project plan. Overall, the project achieved its planned milestones by delivering all core scientific and dissemination outputs as follows.

- A **literature review paper**[1] on image-based PM estimation methods, synthesising existing approaches, data requirements, algorithmic characteristics, and reported performance.
- A **technical note** documenting the implementation and evaluation of representative physics-based, machine-learning, and deep-learning image-based PM estimation methods, including data preparation workflows, model configurations, and accuracy assessment procedures for the Milan case study[2].
- An **open scientific toolkit** released through a public GitHub repository (https://github.com/gisgeolab/aqpictures), including open-source code scripts, analysis-ready datasets, and technical documentation to support method implementation, testing, and replication in other geographic contexts.
- Dissemination activities, including a hybrid **workshop** aimed at introducing the project objectives, methodology, and materials to students and researchers, supported by openly accessible presentation slides and recording (https://github.com/gisgeolab/aqpictureshttps://github.com/gisgeolab/aqpictures/tree/main/references/intro_workshop).
- A **scientific contribution** submitted to, and accepted for publication in, the *ISPRS Archives* for the XXV ISPRS Congress[3], supporting formal dissemination of the project outcomes within the ISPRS community.

[1] The review paper is not publicly attached here due to ongoing journal submission. A draft version is available upon request to authors.

[2] Part of technical note content is currently being arranged into an ISPRS Archives paper accepted for the XXV ISPRS Congress. A draft version is available upon request to authors.

[3] Contribution title: *"Benchmarking and assessment of image-based methods for PM estimation: The AQpictures project"*

3 Outlook and future work

The AQpictures project has established a reproducible framework for benchmarking image-based PM estimation methods, supported by open data, open-source implementations, and general evaluation procedures. While the present project focused on a single metropolitan case study, the developed workflow and scientific toolkit are explicitly designed to support extension, replication, and further validation in other geographic and environmental contexts.

Future work will prioritise multi-site applications across different geographic regions to assess method robustness under different climatic conditions, urban morphologies, background visibility regimes, and pollution sources. Such extensions are expected to provide deeper insight into the transferability and generalisation limits of image-based PM estimation approaches. From a methodological perspective, further developments will explore improved handling of illumination regimes, seasonality, and data heterogeneity, as well as the integration of additional data sources such as low-cost sensors, mobile imagery, and satellite aerosol products. Particular attention will be given to strategies that balance predictive performance with transparency, interpretability, and uncertainty characterisation, in line with emerging best practices in geospatial artificial intelligence. In the longer term, the AQpictures framework can contribute to the development of scalable and complementary air quality monitoring solutions, supporting research, education, and exploratory applications alongside authoritative air quality monitoring networks. Continued maintenance of the open scientific toolkit and engagement with the ISPRS community are finally envisaged to maximise the long-term scientific and societal impact of the project.