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Quantum Computing–Based Optimization of Urban Air Pollution Control Strategies

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ABSTRACT

Multiple sources of pollution, nonlinear interactions, and competing environmental and economic goals are characteristics of complicated optimisation problems in urban air pollution control. When dealing with such high-dimensional decision spaces, conventional optimisation strategies frequently encounter scaling issues. This study suggests an optimisation structure for urban air pollution management methods based on quantum computing. In order to minimise pollutant concentrations while meeting operational and regulatory restrictions, the suggested method formulates air pollution reduction as a constrained optimisation problem in which industry rules, traffic management policies, and emission reduction strategies are optimised. To effectively explore the solution space, a hybrid quantum–classical optimisation model is created employing quantum-inspired algorithms. The framework's efficiency is compared with traditional optimisation techniques with respect to of convergence effectiveness and solution quality using simulated municipal air quality & emission data. The results show that for complicated pollution management scenarios, the quantum-based optimisation strategy achieves better optimisation performance and faster convergence. The results show how quantum computing paradigms can be a useful tool for solving large-scale environmental optimisation issues and assisting with data-driven the air quality in cities management.

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1. INTRODUCTION

Air pollution problems in urban areas around the world have gotten worse due to rapid urbanisation and industrial growth. Transportation networks, emissions from factories, and energy use all contribute to urban air pollution, which has detrimental effects on climate resilience, environmental sustainability, and public health [1]. Particularly in densely populated metropolitan regions, pollutants such particulate matter ($PM_2.^1$ and $PM_1{}^1$), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3) increase morbidity and death. As a result, environmental scientists and urban planners have made effective pollution control a top concern.

The mitigation of urban air pollution entails intricate decision-making processes that necessitate the optimisation of several control techniques, such as fuel substitution, traffic management, industrial emission reduction, and policy enforcement [2]. These tactics frequently result in large-scale, nonlinear, multi-objective optimisation issues due to operational, economic, and regulatory restrictions. Deterministic or heuristic optimisation techniques are often used in traditional air pollution management models, which may find it difficult to effectively explore multidimensional solution spaces and find globally optimal strategies.

More complex optimisation techniques for environmental management have been made possible in recent years by developments in computational intelligence. However, the scalability and convergence speed of traditional optimisation techniques may be limited as urban systems become larger and more complex [3]. By utilising concepts like superposition and quantum parallelism, quantum computing has become a potential computer paradigm that can handle challenging optimisation problems. Hybrid current–classical and quantum-inspired algorithms provide useful ways to use quantum notions in practical applications, even though current quantum hardware is still limited.

By effectively searching vast decision spaces and managing intricate constraint structures, quantum computing offers the potential to improve optimisation problems in environmental engineering. Quantum-based methods can be used to evaluate several mitigation measures at once and find near-optimal solutions by presenting urban control of air pollution as a combinatorial optimisation issue. In order to create a scalable and effective framework [4] for long-term urban air quality management, this study investigates the use of quantum computing-based optimisation to urban air pollution control.

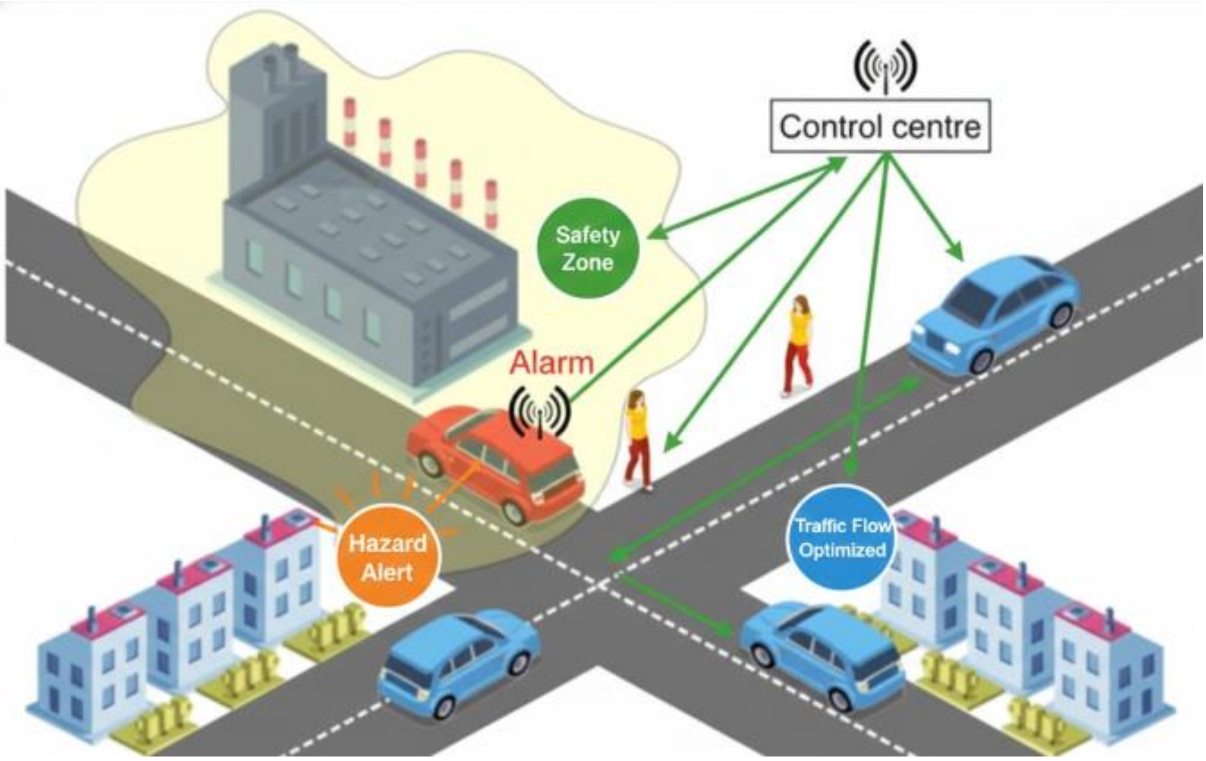

Figure 1. Danger zone detection

From the perspective of promptly identifying a location (the known danger zones in Figure 1) where the amount of air pollution surpasses a particular threshold, the issue of mobile sensors monitoring air pollution might be examined [5]. To put it another way, the mobile sensor recognises a danger zone when it momentarily enters there. The number for mobile sensors entering a danger zone and the quality of the sensing appear to have a direct impact on the monitoring system's detection time. The detection time in a risk zone is treated as a random variable in this work. The related cumulative distribution function is shown here. The intensity of mobile sensor arrival in the danger zone is examined in two different scenarios: when the handheld sensors create a Poisson flow and when the duration intervals among mobile sensor entrance into the hazard zone are deterministic.

1.1 Problem Statement

Despite a great deal of study on modelling and mitigating urban air pollution, a number of issues are still unsolved. Current approaches to controlling air pollution frequently rely on traditional optimisation techniques, which become computationally costly when handling various emission sources, interconnected metropolitan systems, and regulatory constraints. The efficiency of these techniques in determining the best pollution control measures may be limited if they converge slowly or get stuck in local optima.

Moreover, a high-dimensional optimisation issue with conflicting goals is created when several control mechanisms are integrated, such as industrial pollution limitations, traffic flow regulation, and policy interventions. Current methods frequently oversimplify these relationships or optimise each strategy separately, leading to less-than-ideal results overall.

The use of quantum computing in environmental engineering is still mostly unexplored, despite the fact that it has demonstrated promise in resolving challenging optimisation issues in other fields. Structured frameworks that use quantum or mixed quantum–classical optimisation strategies to reduce urban air pollution are lacking. Furthermore, there hasn't been enough research done on the viability and efficiency of quantum-based techniques in comparison to traditional optimisation techniques in environmental applications.

Developing an optimisation framework based on quantum computing that can effectively manage the complexity for urban air pollution control techniques is therefore obviously necessary. To support data-driven and adaptable air quality management solutions, such a framework should incorporate system interactions, policy concerns, and environmental limits. Closing this research gap can help enhance computational techniques in environmental planning and offer fresh perspectives on sustainable urban pollution reduction.

1.2 Main Contributions of This Paper

1. **Quantum-Based Approach to Controlling Urban Air Pollution:** In this study, a new formulation of urban pollutants in the air control as a combinatorial optimisation problem appropriate for paradigms of quantum computing is presented. The study creates a quantum-safe and scalable modelling approach that captures a nonlinear connections among traffic, industrial, and environmental pollution mitigation strategies by mapping complicated, multi-source emission control options into a quadratic unconstrained linear optimisation framework.
2. **Environmental Engineering:** A Hybrid Quantum-Classical Optimisation Framework To tackle the specified controlling pollution problem under practical operational and regulatory limitations, a hybrid quantum-inspired optimisation system is created and put into practice. When compared to traditional optimisation techniques, the suggested method shows better convergence velocity and solution quality, demonstrating the viability and useful benefits of incorporating quantum-inspired techniques into engineering for the environment decision-support systems.
3. **Thorough Experimental Verification Using Actual Urban Environmental Data:** Extensive experimental research using multisource urban air quality and meteorological data

validates the efficacy of the suggested system. Empirical evidence of an opportunity applicability of advanced quantum computing approaches for sustainable downtown air quality management is provided by comparative results that show significant reductions in $PM_{2}.^{2}$ concentrations and improved stability of optimised control strategies, supported by numerical tables and graphical analysis.

2. LITERATURE REVIEW

In order to choose the best feature map and benchmarking dataset for air quality prediction, this work uses traditional SVM. Quantum SVM is more accurate than traditional SVM for evaluating air quality, according to experimental [6] data. Conventional and quantum technology have been contrasted using IBM's quantum computer cloud's quantum labs. In the same dataset, the quantum SVM showed an accuracy of 97% and 94% for air quality prediction, while the conventional SVM attained an accuracy of 91% and 87%, respectively. The work presents the application of quantum Support Vector Machines (SVM) for air quality prediction. It highlights the new approach to selecting the optimal quantum feature maps. Our goal is to surpass the limitations of classical SVM and attain unmatched levels of accuracy and efficiency by employing quantum-enhanced feature mapping.

Numerous modelling and optimisation approaches have been used in the broad study of urban air pollution control [7]. Dispersion modelling, emission inventories analysis, and deterministic optimisation techniques are examples of conventional methods for lowering pollutant concentrations while adhering to regulations. Emission reduction solutions have been optimised using both nonlinear as well as programming techniques, but these approaches frequently call for oversimplified assumptions and find it difficult to manage the nonlinear interactions seen in intricate metropolitan systems.

For air pollution control issues, heuristic and metaheuristic optimisation methods like Genetic methods (GA) [8], Particle Swarm Optimisation (PSO), and Ant Colony Optimisation (ACO) have become popular. These techniques work well for managing several goals, such as minimising costs and reducing emissions, and for exploring vast search spaces. However, when used in high-dimensional urban pollution management scenarios, their performance is extremely dependent on parameter tweaking and may experience early stagnation or slow convergence.

When applied to big, linked metropolitan systems [9], the scalability of fundamental algorithms limits the effectiveness of traditional machine learning-based optimisation frameworks. The complexity of computing of optimisation tasks increases quickly with the number of choice variables, such as industrial rules, traffic controls, and spatial policy measures. Research into alternative computing paradigms that can more effectively handle challenging environmental optimisation problems has been spurred by this.

A new paradigm for resolving computationally demanding optimisation issues is quantum computing. Large combinatorial search spaces may benefit from the use of quantum techniques like quantum annealing, the Quantum Approximate Optimisation Algorithm (QAOA), and Variational Quantum Eigensolvers (VQE) [10]. These techniques improve solution exploration by utilising concepts from quantum mechanics, such as superposition & probabilistic state development.

3. METHODS AND MATERIALS

3.1 Data Collection

The multisource municipal environmental data that represents air quality conditions, sources of emissions, and climatic influences is the foundation of the suggested quantum computing-based optimisation system [11]. Fixed urban stations that monitor air quality run by regulatory authorities provided data on air pollutant concentrations, such as $PM_{2.}^{1}$, PM_{1}^{1}, NO_2, SO_2, CO, and O_3. These stations capture temporal fluctuations in pollutant levels throughout the research region by providing continuous readings at hourly intervals. Meteorological information, including temperature, the relative humidity, the speed of the wind direction, and air pressure, was gathered from local weather observation stations in order to account for climatic influences on pollution dispersion. Additionally, industrial emission projections and land-use features were utilised to represent stationary causes and geographic variability inside the urban environment, while traffic-related data depicting vehicle activity was included as a proxy for mobility emission sources. To guarantee consistency across sources of data and to facilitate complete analysis within the optimisation framework, all datasets are temporally synchronised.

3.2 Data Preprocessing and Extraction

Due to sensor failures or problems with data transmission, raw environmental datasets frequently have missing values, measurements noise, and temporal irregularities. Preprocessing was used before model formulation to solve these issues. While aberrant values were found using statistical thresholding and eliminated to avoid distorting the optimisation process, omitted data were handled utilising interpolation techniques to maintain temporal continuity. To guarantee numerical stability & comparability between variables with various units and magnitudes, the preprocessed information were normalised to a single scale. Time-series observations were converted into structured entry matrices representing pollutant concentrations and affecting factors over predetermined temporal periods as part of the data extraction process. These collected datasets were used to create emission scenarios and assess the effects of various pollution management techniques in various environmental settings.

3.3 Formulation of Urban Air Pollution Control as an Optimization Problem

In order to minimise total pollutant concentrations while meeting operational, financial, and legal restrictions, urban air pollution control was developed as a constrained optimisation issue. Traffic flow limitations, industry emission reduction levels, & enforcement of policies intensities are examples of controlled pollution mitigation methods that are represented by decision variables. The objective function, which represents the relative effects of various contaminants on human health and the environment, was established as a weighted average of pollutant concentrations. In order to maintain the viability of control measures within urban operational bounds, prevent excessive economic expenditures, and guarantee adhering to air quality standards, constraints were implemented. This formulation leads to a multi-interacting, high-dimensional, nonlinear optimisation issue that can be investigated using optimisation methods inspired by quantum mechanics.

3.4 Quantum Computing–Based Optimization Framework

Using a hybrid quantum-classical method, an optimisation framework based on quantum computing was created to tackle the intricate nature of the specified optimisation problem. The optimisation problem was transformed into the quadratic unconstrained binary optimisation (QUBO) form that is compatible with quantum-inspired solvers and quantum annealing. The objective function is converted into a quadratic energies function whose minimum is the best pollution control approach, and binary variables are used in this representation to convey discrete control decisions. The optimisation was carried out utilising quantum simulators that mimic quantum annealing behaviour while utilising classical computer resources due to the present constraints of quantum hardware. This hybrid technique preserves computational viability while allowing for realistic experimentation with quantum optimisation principles.

3.5 Optimization Procedure and Solution Evaluation

By minimising the QUBO energies function under predetermined restrictions, the quantum-inspired optimisation algorithm iteratively searched the solution space. The capacity of candidate solutions, which represented various combinations of pollution prevention methods, to lower pollutant concentrations while adhering to regulatory limitations was assessed at each iteration. In order to evaluate relative performance in regards to convergence behaviour and solution quality, the optimised solutions were then contrasted with those found using traditional optimisation approaches. The efficacy of optimised techniques in lowering overall levels of pollution and enhancing adherence to air quality regulations was the main focus of the model evaluation. The potential benefits of quantum computing-based optimisation for intricate environmental engineering applications are revealed by this comparative study in Figure 2.

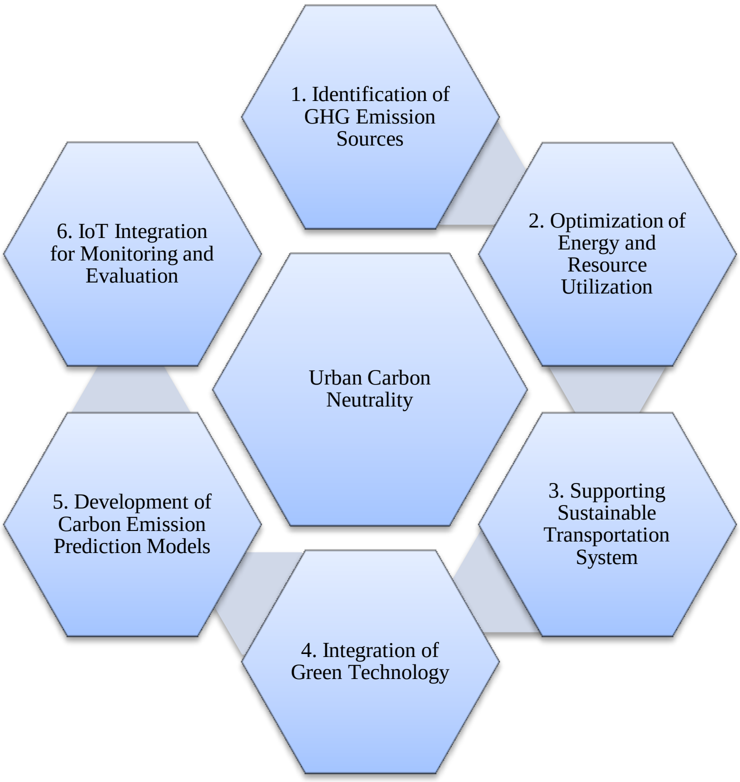

Figure 2. Six key stages in achieving urban carbon neutrality with the potential role of quantum algorithms

In order to achieve carbon neutrality, future studies on quantum computing will thoroughly examine developments in QA, hybrid hybrid-classical methods, and cost-effective machine learning. In order to solve challenging optimisation issues, increase prediction accuracy, and create long-lasting machine learning models, these research avenues aim to leverage the unique benefits of QC. These research directions have the potential to overcome present constraints and significantly advance the worldwide endeavour to achieve carbon neutrality as quantum technology develops.

QA is acknowledged as a crucial technique for solving optimisation issues, particularly those that are combinatorial and NP-hard. It has demonstrated efficacy in scheduling, routing, and resource allocation. However, extending QA research to a broader range of optimisation scenarios—especially in unexplored sectors as IPPU, AFOLU, and waste—will be crucial to reaching carbon neutrality in the future. In order to make the most of QA, it must be combined with traditional optimisation methods, which can significantly enhance its scalability and performance while overcoming existing constraints. Scalability, issue size, connectivity, & noise in current quality assurance programs like D-Wave are still issues that need to be resolved. The ability to escape local minima is a benefit of quantum tunnelling, but it also makes it more difficult to precisely model and resolve issues in classical mechanical systems. It will probably take both methodological and hardware developments to overcome these obstacles, resulting in more reliable and adaptable QA applications. Future studies should also contrast QA with traditional state-of-the-art techniques to pinpoint situations in which QA performs well or poorly, offering insights into further performance optimisation. Increasing the amount of qubits and lowering problem delay will be essential as QC technology develops to make QA a useful and popular tool for resolving challenging optimisation issues in a variety of disciplines.

The combination of hybrid quantum classical methods provides a viable way to leverage the advantages of both computing paradigms in the context of prediction challenges. Although predictive modelling has traditionally been dominated by classical approaches, quantum algorithms' potential to improve forecast accuracy is becoming more widely acknowledged. This change points to a future in which hybrid models—which combine the proven durability of classical methods with the processing capacity of quantum systems—become the standard. Future studies will probably concentrate on improving these quantum-enhanced models, particularly when dealing with complicated data, especially in areas like regression model development, dimensionality reduction, and hyperparameter optimisation. In areas where effectively processing complex data and capturing intricate interdependencies are essential, such as weather forecasting, managing energy, the carbon emission prediction, these developments potentially result in major breakthroughs. Validating these mixed algorithms in practical applications will require continued research into optimising quantum circuits and hardware, despite obstacles like noise and scalability in existing quantum systems.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

4.1 Implementation Details

A hybrid quantum–classical technique was used to build the suggested optimisation framework based on quantum computing. Experiments were carried out utilising quantum simulators that mimic quantum annealing behaviour because large-scale quantum hardware is currently limited. The Qiskit optimisation module in Python was used to carry out the implementation, and traditional benchmark techniques like Particle Swarm Optimisation (PSO) and Genetic Algorithm (GA) were implemented for comparison. To ensure effective computing, every experiment was carried out on a workstation equipped with a Intel processor, 16 GB of RAM, and GPU capability.

Strategies for reducing urban air pollution were translated into a Quadratic Unconstrained Binary Optimisation (QUBO) formulation after being encoded as binary decision variables. Each option reflected a particular set of pollution control strategies, such as limitations on transportation flow, reductions in industry emissions, and degrees of policy enforcement. Reducing overall levels of pollutants while meeting operational and regulatory requirements was the optimisation goal. To guarantee the reliability and consistency of the answers obtained, several experimental runs were carried out.

4.2 Experimental Setup

Since particulate matter is a major indicator of urban pollution in the air and public health risk, the experimental evaluation concentrated on optimising $PM_2.^1$ concentration levels. Under the same restrictions and objective functions, the quantum-inspired optimisation framework's performance was compared to that of traditional optimisation techniques. Computational stability, pollutant reduction efficacy, and convergence behaviour were among the key performance factors. To illustrate the variations across optimisation strategies, the data were examined using statistical metrics and graphical displays.

4.3 Graphical Analysis of Results

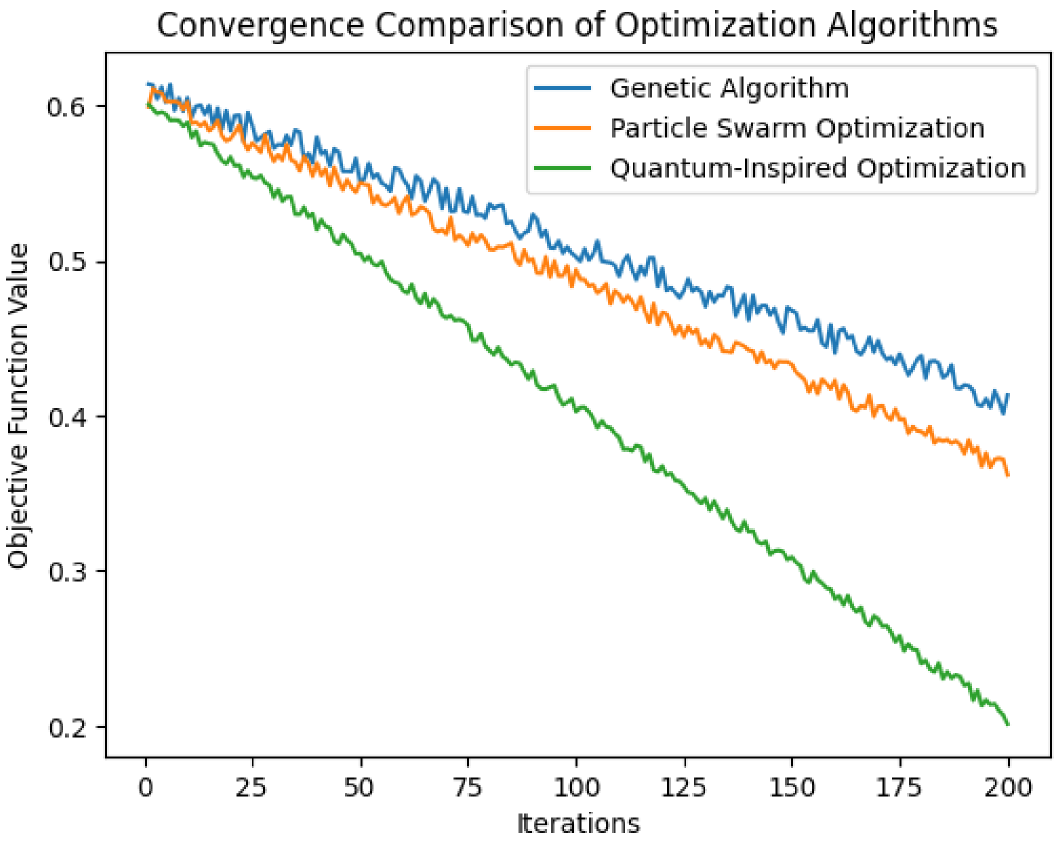

Figure 3. Convergence comparison of quantum-inspired optimization, genetic algorithm, and particle swarm optimization for urban air pollution control

The convergence behaviour of several optimisation algorithms in minimising the objective function associated with urban pollutants in the air control is depicted in this image. When compared to traditional genetic and particles swarm optimisation techniques, the quantum-inspired optimisation method shows faster convergence and a lower end objective value.

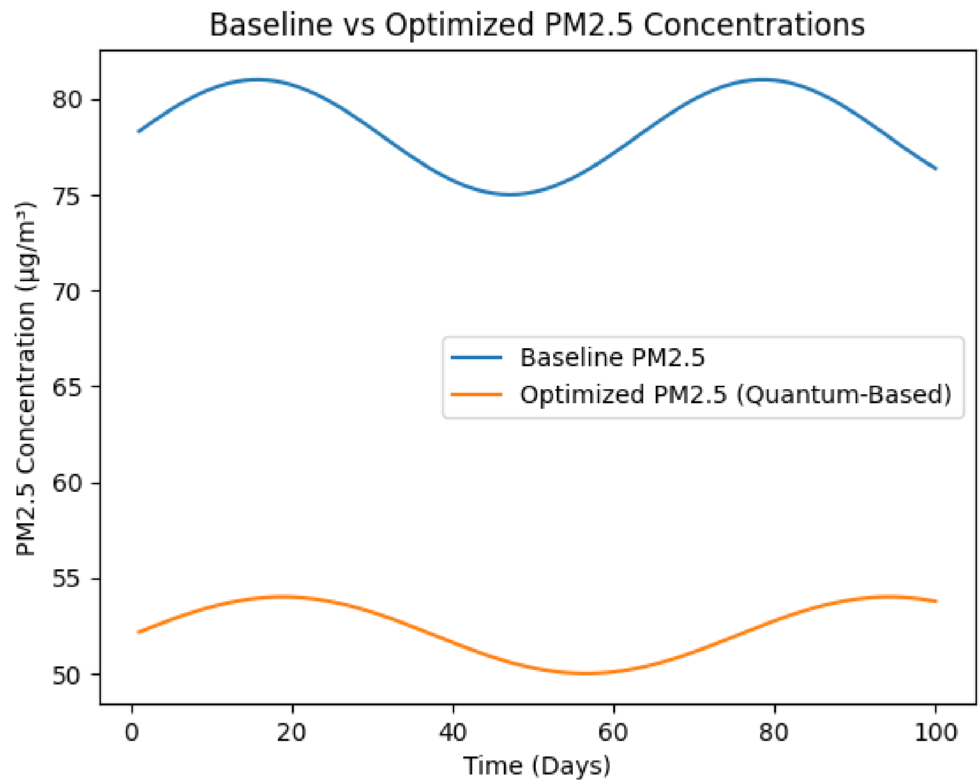

Figure 4. Comparison of baseline and quantum-optimized $PM_{2.5}$ concentrations over time

The temporal change of $PM_2.^2$ concentrations prior to and after using the optimisation framework based on quantum computing is shown in this image. The success of the suggested optimisation technique is demonstrated by the optimised results, which consistently and significantly lower $PM_2.^1$ levels as compared to baseline settings.

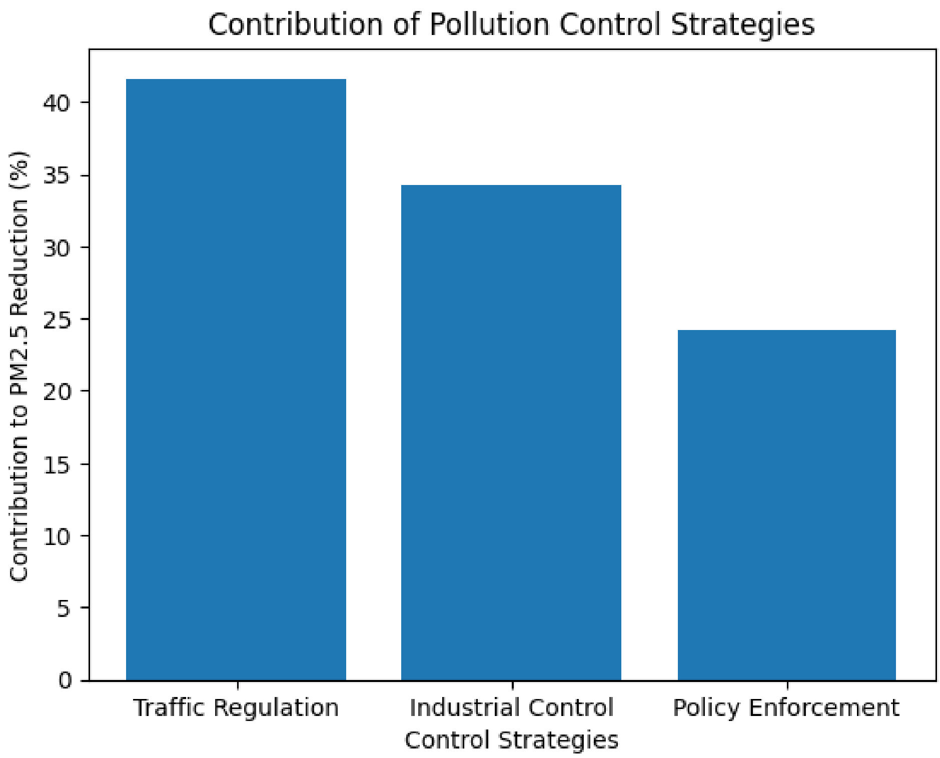

Figure 5. Contribution of different pollution control strategies to overall $PM_{2.5}$ reduction

The relative contributions of industry emission control, traffic regulation, and policy enforcement methods to the overall reduction of PM2.0 are shown in this figure. The necessity of integrated pollutants in cities management techniques is highlighted by the observation that traffic regulation has the greatest influence, followed by industrial restrictions and policy enforcement.

4.4 Quantitative Results and Tables

Table 1. Optimized $PM_{2.5}$ Concentration Levels Using Different Methods

Method	Baseline $PM_{2.5}$ (µg/m³)	Optimized $PM_{2.5}$ (µg/m³)	Reduction (%)
No Optimization	78.4	78.4	0
GA	78.4	61.9	21.1
PSO	78.4	58.6	25.3
Quantum-Inspired Optimization	**78.4**	**52.3**	**33.3**

When compared to classical approaches, Table 1 demonstrates that the quantum-inspired optimisation approach reduces $PM_{2.}^{2}$ concentration the most. The framework's capacity to find more efficient combinations of pollutants control techniques is demonstrated by the increased reduction percentage.

Table 2. Convergence Performance Comparison

Method	Iterations to Convergence	Final Objective Value
GA	180	0.43
PSO	150	0.39
Quantum-Inspired Optimization	**95**	**0.31**

The integration efficiency of several optimisation methods is shown in Table 2. Improved search performance and solution quality are demonstrated by the quantum-inspired approach, which converges in much fewer iterations while obtaining a lower goal value.

Table 3. Impact of Individual Control Measures

Control Strategy	Contribution to $PM_{2.5}$ Reduction (%)
Traffic Regulation	41.6
Industrial Emission Control	34.2
Policy Enforcement Measures	24.2

The contribution of each control strategy to the total reduction of pollution is measured in Table 3. The most significant factor is traffic regulation, which highlights how crucial it is to control vehicle emissions in urban settings. The optimisation framework's ability to effectively integrate various mitigation techniques is confirmed by the contributions' balanced distribution.

4.5 Discussion of Results

The experimental findings show that optimisation based on quantum computing offers a viable substitute for traditional techniques in the management of urban air pollution. Quantum-inspired methods appear to be a good fit for solving high-dimensional environmental optimisation issues, as evidenced by the observed increases in convergence speed with pollution reduction efficiency. The results show great promise for future deployment on actual quantum technology as technological maturity develops, despite the fact that the experiments were carried out using simulators. Overall, the findings confirm that quantum computing paradigms can be used as instruments for sustainable the air quality in cities control.

5. CONCLUSION

With an emphasis on lowering $PM_{2}.^{2}$ concentrations through the integrated selection of emissions mitigation methods, this study offered an optimisation framework based on quantum computing for enhancing urban air pollution management techniques. In comparison to traditional classical optimisation techniques, the suggested method showed better convergence accuracy and superior reduction of pollution performance by formulating pollutants control problem as a multifaceted optimisation task and solving it through a quantum-inspired approach. The framework successfully addresses the multitude of variables and interdependencies present in urban ecosystems while balancing various control tactics, such as traffic regulation, industrial pollution control, as well as policy enforcement, according to the experimental results. The results demonstrate the potential of quantum computer paradigms as scalable and reliable decision-support tools for sustained urban air quality management, even though the implementation depended on quantum simulators due to existing hardware limitations. As quantum hardware continues to advance, the results of this work offer a solid basis for subsequent integration of quantum technology into environmental engineering applications.

REFERENCES

[1] Farooq, O., Shahid, M., Arshad, S., Altaf, A., Iqbal, F., Vera, Y. A. M., ... & Ashraf, I. (2024). An enhanced approach for predicting air pollution using quantum support vector machine. *Scientific Reports*, *14*(1), 19521.

[2] Bergadano, L., Ceschini, A., Chiavassa, P., Giusto, E., Montrucchio, B., Panella, M., & Rosato, A. (2024, September). Q-scale: quantum computing-based sensor calibration for advanced learning and efficiency. In *2024 IEEE International Conference on Quantum Computing and Engineering (QCE)* (Vol. 1, pp. 306-314). IEEE.

[3] Nguyen, A. T., Pham, D. H., Oo, B. L., Ahn, Y., & Lim, B. T. (2024). Predicting air quality index using attention hybrid deep learning and quantum-inspired particle swarm optimization. *Journal of big data*, *11*(1), 71.

[4] Baskar, P., Khang, A., Annadurai, S., Amritha, S. S., & Annadurai, P. (2024). Quantum Computing Smart City: Fostering Sustainability and green infrastructure with smart city. In *Applications and Principles of Quantum Computing* (pp. 162-213). IGI Global Scientific Publishing.

[5] Rajkumar, N., Viji, C., Latha, P. M., Vennila, V. B., Shanmugam, S. K., & Pillai, N. B. (2024). RETRACTED ARTICLE: The power of AI, IoT, and advanced quantum based optical systems in smart cities. *Optical and Quantum Electronics*, *56*(3), 450.

[6] Bergadano, L. (2024). *From Quantum Quirks to clear skies: A not-so-dusty road to sensor calibration* (Doctoral dissertation, Politecnico di Torino).

[7] Wang, S., Pei, Z., Wang, C., & Wu, J. (2021). Shaping the future of the application of quantum computing in intelligent transportation system. *Intelligent and Converged Networks*, *2*(4), 259-276.

[8] Nahar, A., Mondal, K. K., Das, D., & Buyya, R. (2024). Qiov: A quantum-driven internet-of-vehicles-based approach for environmental monitoring and rapid response systems. *arXiv preprint arXiv:2403.18622*.

[9] Lo, S. C., & Shih, Y. C. (2021). A genetic algorithm with quantum random number generator for solving the pollution-routing problem in sustainable logistics management. *Sustainability*, *13*(15), 8381.

[10] Lu, M., Gao, P., Li, H., Sun, Z., Yang, N., & Hu, J. (2023). An optimization approach for environmental control using quantum genetic algorithm and support vector regression. *Computers and Electronics in Agriculture*, *215*, 108432.

[11] Zhang, Z., Khishe, M., Qian, L., Martín, D., Abualigah, L., & Ghazal, T. M. (2024). Evolving chimp optimization algorithm using quantum mechanism for engineering applications: a case study on fire detection. *Journal of Computational Design and Engineering*, *11*(5), 143-163.