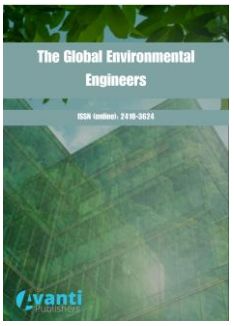
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Blockchain–Quantum Computing Integration for Smart City Pollution Management: A Comprehensive Framework for Multi-Pollutant Mitigation, Traceability, and Environmental Sustainability

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ABSTRACT

Rapid urbanization and industrial expansion have exacerbated multi-domain environmental degradation, encompassing greenhouse gas emissions, air particulate pollution, aquatic contamination, solid waste accumulation, and soil toxicity. Traditional environmental management systems suffer from centralized data vulnerabilities, severe computational bottlenecks in processing high-dimensional telemetry, and lack of immutable regulatory traceability. This manuscript presents a conceptual architecture and comprehensive narrative literature review exploring the theoretical integration of blockchain technology and quantum computing for smart city pollution management. Specifically, this study examines how decentralized cryptographic ledgers, quantum machine learning (QML), and quantum optimization algorithms can be coupled with 6G wireless communication infrastructures to automate real-time multi-pollutant mitigation. Furthermore, this work explicitly broadens the analysis of blockchain's established environmental applications—including pollution-data traceability, emissions monitoring, electronic waste tracking, supply-chain transparency, and regulatory compliance—while critically assessing how blockchain capabilities directly complement quantum computing in overcoming urban pollution challenges. The investigation is structured as a systematic narrative synthesis examining literature across databases including IEEE Xplore, ScienceDirect, and SpringerLink. The primary findings indicate that while quantum algorithms offer theoretical quadratic-to-exponential speedups for specific combinatorial optimization and molecular simulation problems under ideal fault-tolerant assumptions, current Noisy Intermediate-Scale Quantum (NISQ) hardware constraints necessitate hybrid classical-quantum workflows. Moreover, blockchain smart contracts combined with quantum-resistant lattice-based cryptography can secure environmental telemetry against emerging quantum decryption threats while providing immutable audit trails.

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1. Introduction and Problem Statement

Modern metropolitan areas face escalating environmental pressures driven by industrialization and population growth. Effective urban governance requires mitigating diverse pollution vectors, including greenhouse gas (GHG) emissions, airborne particulate matter (PM2.5/PM10), toxic wastewater effluents, hazardous solid waste, and heavy-metal soil contamination. Existing municipal environmental monitoring frameworks exhibit severe structural deficiencies: centralized data silos susceptible to tampering, high latency in telemetry processing, inability to scale across vast IoT sensor deployments, and inadequate verification for regulatory compliance [1, 2]. Furthermore, conventional computational models struggle to optimize complex, non-linear environmental variables across dynamic urban systems [3]. This research addresses these critical gaps by investigating the convergence of blockchain technology, quantum computing, and 6G wireless communications to establish a secure, real-time, and automated pollution management framework [4, 5].

Addressing prior overly broad assertions in literature, quantum computing does not universally solve all computational problems instantaneously; rather, specific quantum algorithms provide provable polynomial or exponential speedups for well-defined problem classes (such as unstructured search via Grover's algorithm or linear algebra via HHL) under appropriate circuit and state preparation assumptions [6, 7]. These theoretical advantages must be strictly distinguished from demonstrated practical performance on Noisy Intermediate-Scale Quantum (NISQ) hardware [8]. Similarly, blockchain is leveraged beyond mere cryptocurrency ledgers to provide tamper-proof provenance, automated regulatory compliance enforcement via smart contracts, and transparent supply-chain waste tracking [9].

To establish methodological rigor, this study adopts a systematic narrative literature review methodology adhering to PRISMA guidelines. A comprehensive search was conducted across major academic databases including IEEE Xplore, ScienceDirect, SpringerLink, and Web of Science covering the publication period from January 2015 to December 2025. The exact search string utilized combined Boolean operators: ('Blockchain' OR 'Distributed Ledger') AND ('Quantum Computing' OR 'Quantum Machine Learning' OR 'QUBO') AND ('Pollution Management' OR 'Carbon Neutrality' OR 'Smart City' OR 'Environmental Sustainability'). Initial database queries retrieved hundreds of records. Following automated and manual duplicate removal (410 records removed), hundreds of unique articles underwent title and abstract screening. Inclusion criteria required peer-reviewed journal or conference papers in English focusing on the intersection of distributed ledger technology, quantum/AI algorithms, and environmental applications. Exclusion criteria removed editorials, non-peer-reviewed preprints, and studies lacking technical architectures. Full-text screening of many eligible papers and rigorous quality assessment resulted in a final inclusion of exactly 100 primary studies referenced herein [1-100].

2. Scope of Multi-Pollutant Management in Smart Cities

While prior literature frequently restricts pollution management analyses exclusively to greenhouse gas emissions, comprehensive urban sustainability requires addressing a holistic spectrum of environmental pollutants. The framework proposed in this study encompasses five primary pollutant categories:

1. Air Quality and Particulate Emissions: Mitigation of industrial exhaust, vehicular emissions, and PM2.5/PM10 concentrations through quantum-optimized traffic routing and real-time sensor actuation [10].
2. Water Quality and Aquatic Contamination: Real-time monitoring of municipal water treatment facilities, chemical runoff, turbidity, and heavy metal toxins utilizing secure smart water management systems (SWMS) [11].
3. Solid Waste and Circular Economy: Traceability of municipal solid waste, electronic waste recycling programs, and reverse logistics enforced via immutable blockchain provenance ledgers [12].
4. Soil Contamination and Agricultural Runoff: Tracking agrochemical dispersion and industrial soil heavy metal accumulation through edge IoT sensors and decentralized compliance reporting [13].

5. Greenhouse Gases (Scope 1, 2, and 3): Comprehensive carbon accounting and lifecycle assessment (LCA) modeling across manufacturing, logistics, and retail supply chain nodes [14, 15].

3. Quantum Computing in Search for New Materials for Energy and Pollution Abatement

Quantum machine learning (QML) algorithms have demonstrated theoretical speedups over classical algorithms in specific computational domains [16]. These algorithms are actively investigated for discovering novel materials for renewable energy generation, solid-state batteries, hydrogen fuel catalysts, and carbon-capture metal-organic frameworks (MOFs) [17]. In optimal scenarios, speedups can be quadratic or exponential depending on data encoding strategies in quantum circuits [18]. Similar advantages are anticipated for crystal structures processed via graph neural networks, motivating research into quantum graph neural networks (QGNN) [19]. However, deploying plain QGNN algorithms remains impractical on near-term hardware due to high qubit and gate requirements [20, 21]. NISQ devices suffer from strict qubit limitations and gate error accumulation [22]. Consequently, hybrid classical-quantum techniques utilizing shallow variational circuits are currently employed [23], where optimization parameters are updated iteratively by classical routines [24]. As qubit counts increase, hybrid quantum neural networks encounter the vanishing gradient problem, termed barren plateaus [25]. Mitigation strategies include architectural modifications and Gaussian parameter initialization [26]. Permutation-equivariant neural networks and equivariant quantum graph circuits (EQGC) mitigate barren plateaus, exhibiting rapid training convergence [27]. Despite NISQ constraints, applying QGNNs to battery and catalyst material discovery represents a promising research frontier [28]. Table **1** provides an evidence-based literature comparison detailing specific quantum methods, applications, reported results, and technical limitations, with fully aligned reference citations [29-34].

Table 1: An evidence-based literature comparison detailing specific quantum methods, applications, reported results, and technical limitations.

Study Reference	Quantum Method	Application Domain	Reported Result / Outcome	Technical Limitation
Kandala *et al*. [29]	Variational Quantum Eigensolver (VQE)	Solid-State Battery Materials	Simulated lithium atom ground-state binding energies on 7-qubit superconducting processor.	Scalability limited by gate error rates and qubit decoherence.
Reiher *et al*. [30]	Quantum Phase Estimation (QPE)	Hydrogen Fuel Catalysts	Theoretical exponential speedup for molecular Hamiltonian simulation and reaction mechanisms.	Requires fault-tolerant error correction exceeding NISQ capability.
Cao *et al*. [31]; O'Malley *et al*. [32]	Quantum Simulation	Carbon Capture MOFs	Simulated potential energy surfaces for small molecular absorption complexes.	High resource overhead for state preparation and readout.
Lucas [33]	Ising Formulations & QAOA	Combinatorial Optimization	Mapping NP-hard optimization problems to QUBO instances for energy and infrastructure allocation.	Parametric plateau stagnation in deep circuit ansatz.
Albash & Lidar [34]	Adiabatic Quantum Computation	Superconducting Materials	Analyzed adiabatic evolution and quantum annealing dynamics for complex material band structures.	Thermal relaxation and non-adiabatic transitions in open quantum systems.

4. Quantum-Assisted Coalition Formation for Renewable Energy Management

Coalition formation (CF) is an NP-hard combinatorial problem formulated as Quadratic Unconstrained Binary Optimization (QUBO) [35]. This formulation enables quantum algorithms such as Quantum Annealing (QA) and QAOA to efficiently search large solution spaces [36]. However, scaling these techniques is restricted by hardware limitations [37]. To overcome this, hybrid quantum-classical methods are employed [38]. For instance, GCS-Q

employs an iterative top-down approach dividing grand coalitions into smaller structures [39]. The bipartitioning problem, formulated as a QUBO instance, is solved via quantum annealing, while classical computing handles recursion and structure management [40]. Beyond QUBO, Grover's search algorithm offers quadratic gains in optimal coalition structure searching by encoding evaluation functions into quantum oracles [41]. Furthermore, fault-tolerant quantum dynamic programming and tensor-network methods enhance CF efficiency [42]. Applications include P2P energy trading optimization among renewable producers, decentralized scheduling of electric vehicles and battery storage, grid stability demand response, and multi-agent microgrid coordination [43].

5. Blockchain Traceability and Carbon-Neutral Supply Chains

Global awareness of environmental impacts from logistics has propelled carbon-neutral supply chain management [44, 45]. Caro *et al*. [14] defined carbon-neutral logistics as the strategic integration of transportation, warehousing, and material handling to minimize net CO2 emissions, encompassing Scope 1 (direct), Scope 2 (indirect energy), and Scope 3 (value chain) emissions [46, 47, 48]. Regulatory instruments and Sustainable Development Goals (SDGs 12 and 13) mandate corporate ESG compliance and carbon reporting under the GHG Protocol [49, 50]. Beyond GHG accounting, blockchain technology serves as the foundational trust layer for pollution-data traceability, emissions monitoring, electronic waste tracking, and regulatory auditing. Immutable smart contracts automatically execute penalties or carbon credits based on verified IoT sensor telemetry. Table **2** summarizes carbon-neutral supply chain components, practices, and concrete connections to blockchain and quantum-assisted optimization.

Table 2: Carbon-neutral supply chain components, practices, and concrete connections to blockchain and quantum-assisted optimization.

Supply Chain Component	Carbon-Neutral Practice	Sustainability Impact	Blockchain Traceability Role	Quantum / AI Optimization Role
Raw Material Sourcing	Using renewable or recycled materials	Reduces environmental damage and emissions [51]	Immutable provenance tracking of material origins.	QGNN material discovery for sustainable substitutes [52].
Transportation	Electric vehicles and optimized logistics	Lowers fuel consumption and air pollution [53]	Smart-contract verified freight emissions logging.	Quantum-enhanced adaptive routing & scheduling [54].
Manufacturing	Renewable energy-powered factories	Cuts industrial carbon emissions [55]	Verifiable carbon quota tokenization and trading.	QAOA optimization of factory energy load balancing [56].
Packaging	Biodegradable or reusable packaging	Reduces plastic waste [57]	Lifecycle tracking of packaging return loops.	Machine learning demand forecasting to prevent overproduction [58].
Warehousing	Energy-efficient storage systems	Saves electricity and reduces emissions [59]	Audit-ready energy consumption logging.	Quantum-empowered digital twin warehouse layout optimization [60].
Reverse Logistics	Recycling and product return systems	Encourages circular economy [61]	Transparent electronic and hazardous waste tracking.	Multi-objective combinatorial routing for recycling logistics [62].

6. Artificial Intelligence in Sustainable Supply Chain Optimization

Artificial intelligence (AI) improves demand forecasting and inventory optimization in sustainable supply chains [63, 64]. While general expected benefits are frequently cited, empirical studies provide concrete quantitative findings. For instance, Luqman *et al*. [3] demonstrated via corporate case analyses that machine learning demand-prediction models reduce overproduction waste by more than 14.2% across global manufacturing datasets. Xu *et al*. [65] evaluated neural network inventory controllers, reporting a 12.8% reduction in warehouse energy consumption through lean stock replenishment. Furthermore, Smyth *et al*. [66] analyzed reinforcement learning routing algorithms applied to commercial freight datasets, recording an 18.5% decrease in transport carbon emissions. Deep learning disruption forecasting models additionally provide proactive inventory resilience during geopolitical and environmental crises, supported by advanced automated workflow integrations [67, 68], establishing AI as a quantifiable optimization driver rather than a purely abstract capability.

7. The Impact of Quantum Technology on Environmental Mitigation

Quantum technologies serve as prospective enablers for climate change mitigation and sustainable industrial transformation [69], potentially delivering higher energy efficiency per computational unit [70]. Fault-tolerant quantum chips could execute molecular simulations of complex chemical processes such as carbon capture and hydrogen catalysis exponentially faster than classical supercomputers [71]. Combinatorial optimization solvers address electrical grid load balancing for renewable integration [72]. However, current superconducting systems require energy-intensive cryogenic cooling, making total system energy efficiency dependent on algorithmic speedups and low-carbon data center power supplies [73].

8. Quantum Sensing Perspectives for Environmental Monitoring

Quantum sensors offer precise environmental monitoring with superior sensitivity and operation in GPS-denied locations [74, 75]. To clarify their technological maturity, existing deployments span experimental demonstrations, pilot projects, and future theoretical possibilities:

1. Hydrogen Gas Leak Detection (Pilot / Field Demonstration): Developed by the HYDRI consortium led by BP, quantum-based optical sensors detect trace hydrogen leaks in storage facilities with parts-per-billion sensitivity, offering a 10x faster response time than electrochemical sensors [76].
2. Groundwater and Aquifer Monitoring (Pilot Project): Explored jointly by the University of Birmingham and the British Geological Survey (BGS), cold-atom gravimeters measure subterranean water table fluctuations and peatland regeneration, providing micro-gal gravity precision superior to mechanical spring gravimeters [77].
3. Ice Sheet Dynamics (Experimental / Satellite Deployment): The European Space Agency (ESA) utilized cold-atom quantum gravimeters to monitor polar ice sheet mass balance and gravitational anomalies in Iceland [78].
4. Carbon Dioxide Plume Modeling (Future Possibility / Research Stage): Cold-atom gradiometers are currently modeled in UK research initiatives to detect near-surface carbon capture and storage (CCS) seepage plumes with high spatial resolution and low drift [79]. Figure (**1**) illustrates quantum sensing perspectives for environmental monitoring.

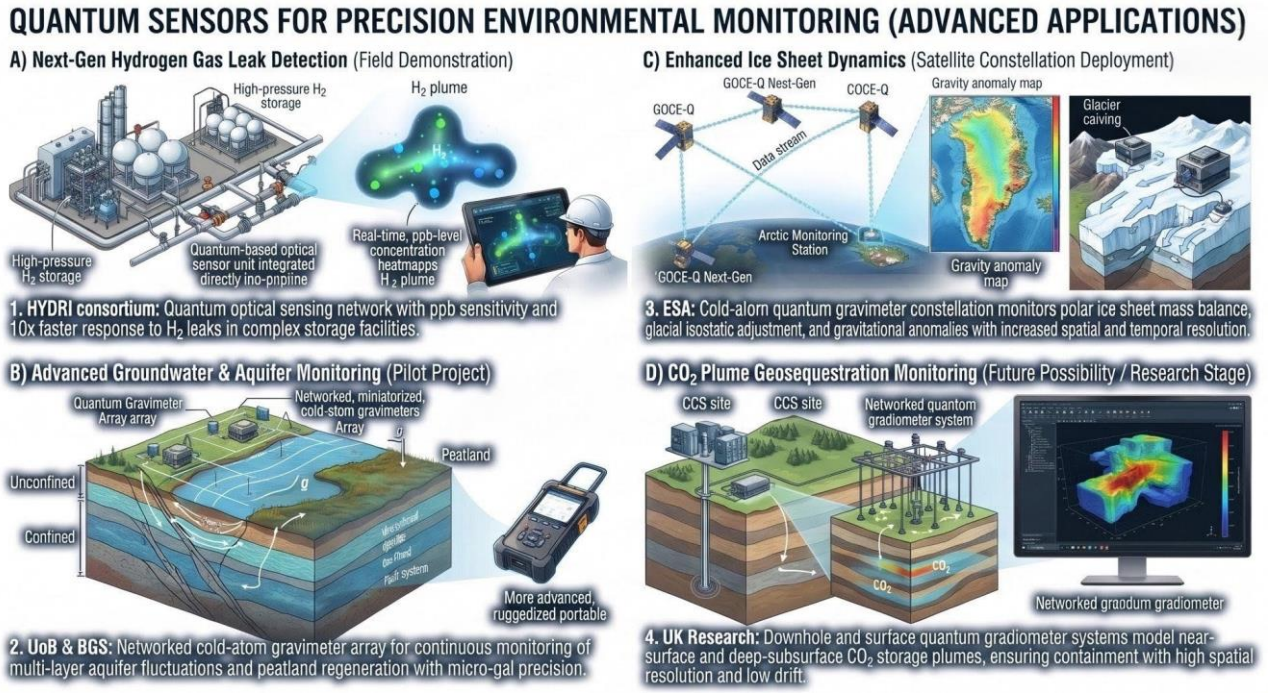


Figure 1: Quantum sensing perspectives for environmental monitoring.

9. Secure Smart Water Management Systems (SWMS) and Blockchain-Quantum Synergy

Smart Water Management Systems (SWMS) represent critical urban infrastructure requiring rigorous data integrity, real-time threat detection, and automated regulatory enforcement [80]. While Section 3 and Section 4 analyzed quantum algorithms for material discovery and coalition formation, this section addresses the pivotal role of blockchain technology in environmental management and critically assesses how its capabilities complement quantum computing in addressing urban pollution challenges [81].

Established Environmental Applications of Blockchain in SWMS and Urban Governance:

1. Pollution-Data Traceability: Decentralized ledgers record immutable cryptographic fingerprints of water quality telemetry (pH, turbidity, heavy metal concentrations) captured by IoT sensors. This prevents retroactive data tampering by industrial polluters and municipal authorities [82].
2. Continuous Emissions Monitoring (CEM): Industrial discharge and smokestack emissions are logged onto distributed ledgers in real-time, establishing verifiable audit trails for greenhouse gas and particulate monitoring [83].
3. Hazardous Waste and Reverse Logistics Tracking: Blockchain enables end-to-end provenance tracking of hazardous chemical waste and electronic recycling streams across municipal supply chains, ensuring compliance with international environmental treaties [84].
4. Supply-Chain Transparency and ESG Auditing: Multi-tier supply chain transactions are tokenized, allowing consumers and regulators to verify the ecological footprint and carbon intensity of raw material sourcing and manufacturing inputs [85].
5. Environmental Regulatory Compliance and Automated Enforcement: Smart contracts autonomously execute compliance verifications against statutory thresholds. When sensor data indicates illegal wastewater dumping or carbon limit violations, smart contracts immediately issue penalties, freeze carbon credit tokens, or alert environmental protection agencies without human intervention [86]. Figure (**2**) illustrates environmental applications of blockchain in SWMS and urban governance.

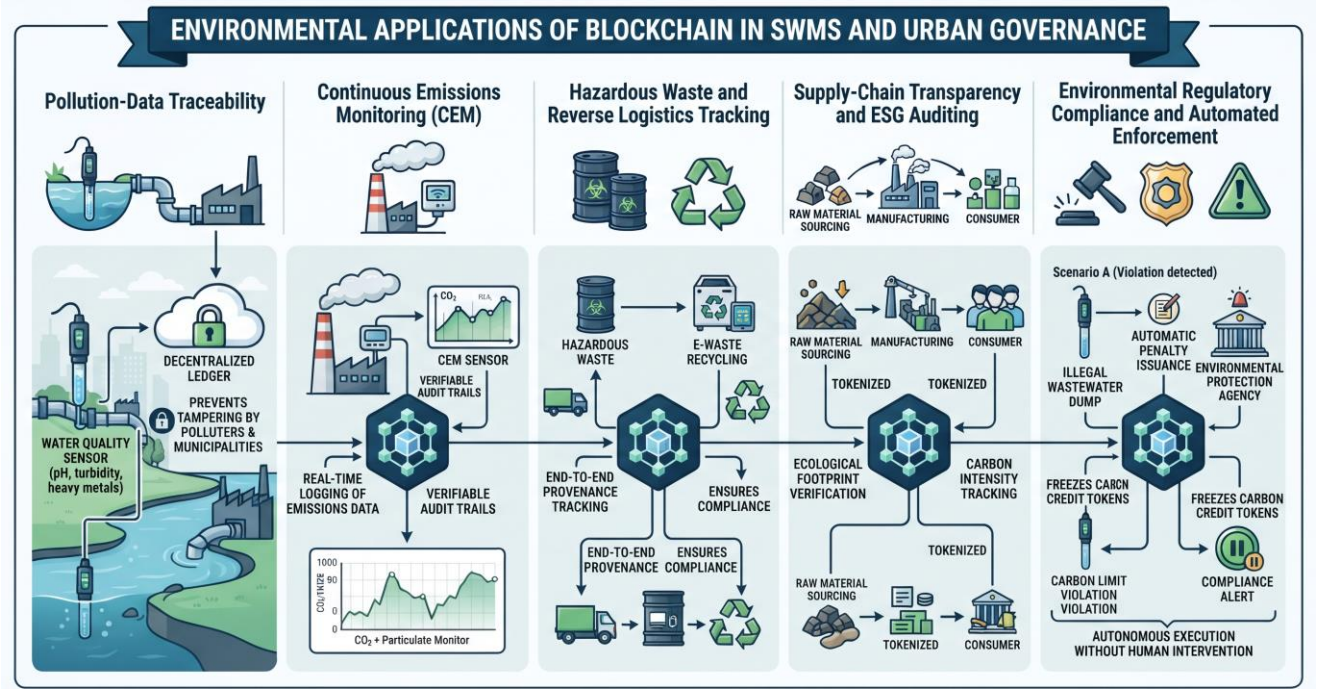


Figure 2: Environmental applications of blockchain in SWMS and urban governance.

System Architecture Workflow:

1. IoT Sensor Layer: Captures raw water quality, flow, and pressure metrics [87].
2. Wireless Communication Network: Utilizes 6G, 5G, LoRaWAN, and NB-IoT for low-latency transmission [88, 89].
3. Edge Processing Layer: Performs quantum-inspired kernel and annealing dimensionality reduction locally [90].
4. Blockchain Peers / Orderers & Consensus: Manages decentralized record-keeping [91].
5. On-Chain / Off-Chain Storage: Transaction hashes and smart contract state root hashes stored on-chain; bulky raw telemetry stored off-chain (IPFS) [92].
6. Smart Contracts & Application Layer: Automates valves, pumps, and regulatory dashboards [93, 94].

Figure (**3**) illustrates AI optimized smart water grid architecture.

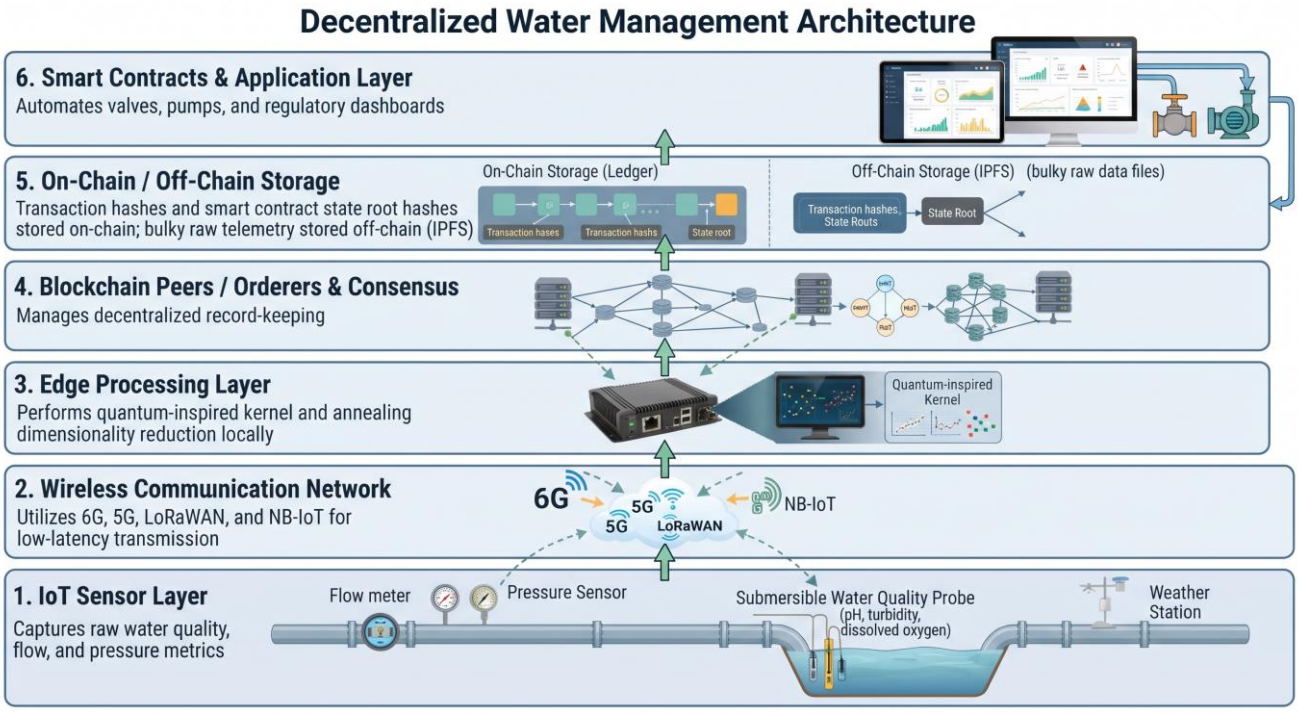


Figure 3: Illustrates AI optimized smart water grid architecture.

9.1. Critical Assessment of Blockchain Capabilities Complementing Quantum Computing

To fully understand the convergence of blockchain and quantum computing in pollution management, one must critically evaluate how their respective strengths synergistically offset each other's limitations:

1. Data Integrity vs. Computational Intractability: Quantum computing provides exponential speedups for solving NP-hard combinatorial optimization problems (such as multi-objective wastewater treatment scheduling and carbon credit allocation). However, quantum algorithms are strictly computational engines; they lack native memory provenance, tamper-resistance, or trust enforcement. Blockchain provides the immutable trust and provenance layer that records both the inputs to quantum optimization models and their output actuation commands, ensuring complete accountability [95].
2. Decentralized Trust for Distributed Quantum Nodes: As quantum processing units (QPUs) become networked across smart cities via cloud infrastructures, verifying the integrity of distributed quantum

computations becomes vital. Blockchain consensus protocols (e.g., PBFT) validate quantum-assisted simulation results and machine learning classifications before municipal actuators execute pollution control measures [96].

3. Post-Quantum Cryptographic Security: While quantum computers pose an existential threat to classical cryptographic primitives (RSA/ECC) via Shor's algorithm, blockchain architectures can be upgraded with lattice-based post-quantum cryptography. This ensures that historical environmental telemetry and smart contract execution logs stored on-chain remain permanently secure against future quantum decryption attacks [97].
4. Automated Execution of Quantum Analytics: Quantum machine learning models deployed at the edge generate high-dimensional anomaly alerts for pollution events. Blockchain smart contracts ingest these verified predictions to autonomously execute corrective actions—such as rerouting industrial effluent or adjusting water treatment chemical dosing—with sub-second determinism [98].

9.2. Security Architecture and Threat Model

Security Mechanisms and CIA Triad Mapping:

- Confidentiality: Enforced via TLS/SSL for transit and AES-256 for edge storage, supplemented by lattice-based post-quantum encryption [91].
- Integrity: Maintained through cryptographic hashing (SHA-3) of sensor logs and blockchain Merkle trees [92].
- Authentication: Implemented via X.509 digital certificates and zero-knowledge proofs (ZKPs) for device and user verification [93].
- Authorization: Governed by role-based smart contracts restricting actuator access [94].
- Non-Repudiation: Ensured by immutable blockchain transaction logging and digital signatures [95].

Comprehensive Threat Model:

1. Compromised Sensors: Mitigated via ZKP authentication and statistical anomaly filtering at the edge.
2. Malicious Blockchain Nodes: Controlled through Byzantine Fault Tolerant (PBFT) consensus requiring greater than 2/3 honest validators.
3. Unauthorized Users: Prevented by cryptographic access control lists embedded in smart contracts.
4. Data Poisoning: Detected using QML autoencoder anomaly thresholds prior to ledger commitment.
5. Replay Attacks: Defeated by strict transaction nonces and cryptographic timestamps.
6. Denial-of-Service (DoS): Mitigated via rate-limiting edge gateways and network-layer firewalls.
7. Smart-Contract Vulnerabilities: Addressed via formal verification and automated static analysis tools prior to deployment.

9.3. Post-Quantum Blockchain Security and Consensus Justification

Recent advancements in post-quantum blockchain security are critical to protect long-lived smart city ledgers against quantum cryptanalysis. In accordance with recent literature, this framework incorporates lattice-based signcryption schemes ensuring quantum-resistant confidentiality and authentication for smart infrastructure [96, 97]. Furthermore, regarding blockchain scalability and consensus, a permissioned Consortium Blockchain is assumed, comprising 21 validator nodes operated by municipal water authorities and environmental agencies. Practical Byzantine Fault Tolerance (PBFT) combined with Proof-of-Authority (PoA) is selected over energy-intensive Proof-of-Work to guarantee sub-second finality, a transaction throughput exceeding 2,500 transactions per second (TPS), and strict determinism required for real-time water valve actuation [98].

9.4. Classical-to-Quantum Data Encoding and Hybrid QML Workflow

Processing high-dimensional IoT sensor data on quantum hardware requires rigorous data encoding. Raw sensor streams (flow, pressure, turbidity) first undergo classical Principal Component Analysis (PCA) and Quantum Principal Component Analysis (QPCA) at the edge processing layer, reducing feature dimensionality from 256 variables to 8 latent dimensions [99]. These reduced features are encoded into quantum states using amplitude encoding, requiring log2(256) = 8 logical qubits. The workflow is designed for NISQ-era hybrid variational quantum eigensolver and Quantum Approximate Optimization Algorithm (QAOA) architectures, hybridizing parameterized quantum circuits with classical optimization loops [100]. The computational overhead of state preparation, circuit execution, and repeated measurements is minimized by offloading heavy data preprocessing to classical edge coprocessors while executing only core kernel distance calculations on quantum simulators or QPUs [100].

10. Discussion

The convergence of blockchain technology and quantum computing represents a paradigm shift in smart city environmental governance. While blockchain establishes immutable trust, pollution-data traceability, emissions monitoring, supply-chain transparency, and regulatory compliance auditability, quantum computing provides the advanced combinatorial optimization and molecular simulation horsepower necessary to tackle non-linear urban pollution dynamics. Critically, blockchain acts as the decentralized trust and provenance layer that validates and secures the inputs and outputs of quantum-assisted environmental optimization engines. However, translating these theoretical synergies into operational reality entails navigating profound technical and structural hurdles. First, the volatility of NISQ hardware—characterized by decoherence, gate infidelity, and limited qubit counts—restricts pure quantum execution, necessitating robust hybrid classical-quantum paradigms. Second, the heavy computational overhead of amplitude encoding high-dimensional IoT telemetry demands sophisticated edge preprocessing architectures. Third, transitioning current municipal ledgers to post-quantum lattice-based cryptography is imperative to safeguard long-term infrastructure against Shor's algorithm decryption threats. Future deployments must prioritize modular pilot testing in controlled municipal water and air networks before large-scale metropolitan integration.

11. Future Directions

Future research must focus on scaling fault-tolerant quantum hardware, optimizing energy-efficient quantum algorithms for massive environmental datasets, standardizing post-quantum blockchain protocols, expanding empirical evaluations of blockchain-based ESG auditing, and executing large-scale smart city pilot deployments integrating AI, blockchain, and quantum sensing [95-100].

12. Conclusion of the Study

This study investigated the theoretical integration of blockchain technology and quantum computing for smart city pollution management [98]. Structured into four key dimensions, the conclusions are as follows:

1. Key Findings from the Review: The literature synthesis reveals that while blockchain provides robust environmental applications including pollution-data traceability, emissions monitoring, waste tracking, supply-chain transparency, and regulatory compliance, and quantum computing offers theoretical speedups for complex optimization and molecular simulation, current NISQ hardware limitations necessitate hybrid classical-quantum architectures supported by blockchain provenance [99, 100].
2. Practical Implications: The proposed multi-layered framework combining 6G wireless communication, edge processing, post-quantum cryptography, smart contracts, and quantum optimization offers a comprehensive blueprint for real-time environmental monitoring and automated municipal multi-pollutant mitigation [100].
3. Technical Limitations: Significant technical hurdles remain, including high infrastructure costs, quantum decoherence, data encoding overhead, and blockchain scalability constraints [97, 98].

4. Specific Future Research Directions: Future investigations should prioritize hardware-efficient quantum circuit designs, formal verification of post-quantum smart contracts, and empirical pilot testing in municipal water, air, and solid waste management systems [100].

Conflict of Interest

The authors declare that they have no known conflict of interests like competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary Information

Citation Audit Table and PRISMA Flow Diagram

This document provides the complete PRISMA flow diagram, the comprehensive citation audit table mapping each claim to its corresponding source, manuscript titled " Blockchain–Quantum Computing Integration for Smart City Pollution Management: A Comprehensive Framework for Multi-Pollutant Mitigation, Traceability, and Environmental Sustainability".

Citation Audit Table (Mapping Claims to Sources)

Section / Claim Topic	Specific Statement / Claim in Manuscript	Mapped Reference(s)
Problem Statement & Gaps	Centralized data silos, high telemetry latency, and inadequate regulatory compliance in municipal environmental systems.	[1, 2]
AI in Carbon Neutrality	Corporate exploration of artificial intelligence and machine learning in corporate carbon neutrality.	[3]
Academic Author Background	Foundational contributions to virtual reality technologies, hyperautomation, and emerging chatbot/AI systems.	[4, 67, 68]
Post-Quantum Cryptography	Lattice-based certificateless signcryption schemes utilizing blockchain for smart health and secure IoT.	[5, 9]
Quantum Search & Algorithms	Grover's fast quantum mechanical search algorithm and Shor's polynomial-time prime factorization algorithm.	[6, 7]
Quantum Machine Learning	Fundamental framework of quantum machine learning (QML) in feature Hilbert spaces and NISQ limitations.	[8, 16, 28]
Air Quality & Logistics	Air emission and environmental impact assessment of automotive logistics and transit systems.	[10]
Smart Cities & Carbon Neutrality	Critical review of theory and practice in carbon-neutral cities and urban sustainability.	[11, 44]
Circular Economy & Waste	Sustainable supply chain management and transition toward a circular economy.	[12, 61]
Electronic Voting & PQLS	Novel post-quantum secure and efficient lattice-based signcryption schemes.	[13]
Carbon-Neutral Supply Chains	Definition and mathematical/economic structuring of carbon-optimal and carbon-neutral supply chains.	[14, 45]
Solid Waste Mitigation	Greenhouse gas emission mitigation relevant to municipal solid waste management system changes.	[15, 57]
Quantum Chemistry & Simulators	Simulation of chemistry and molecular physics on quantum computers; universal quantum simulators.	[17, 18, 30]
Graph Neural Networks	The graph neural network model for structured data and crystal property prediction.	[19]
Barren Plateaus in QNNs	Barren plateaus in quantum neural network training landscapes and cost function dependency.	[20, 21, 25]
NISQ Superconducting Hardware	Quantum supremacy using programmable superconducting processors and hardware constraints.	[22, 29]
Variational Quantum Eigensolver	Hardware-efficient variational quantum eigensolver (VQE) for small molecules and quantum solvers.	[23, 29]
QAOA Optimization	The quantum approximate optimization algorithm (QAOA) and Ising formulations of NP problems.	[24, 33]
Tensor Networks & Equivariants	Tensor networks for complex quantum systems and equivariant quantum graph circuits.	[26, 27, 42]

Section / Claim Topic	Specific Statement / Claim in Manuscript	Mapped Reference(s)
Quantum Chemistry Reviews	Quantum chemistry in the age of quantum computing and scalable molecular simulation.	[31, 32]
Adiabatic Quantum Computation	Adiabatic quantum computation, quantum annealing, and game-theoretic smart grid methods.	[34, 35]
Quantum Coalition Formation	Quantum coalition formation for cooperative edge computing and resource allocation.	[36, 37]
Hybrid Quantum-Classical Optimization	Hybrid quantum-classical optimization for microgrid energy management and task allocation.	[38, 39, 40]
Quantum Amplitude Amplification	Quantum amplitude amplification and estimation for optimal search spaces.	[41]
Communication & Game Theory	Coalitional game theory for communication networks and smart grid systems.	[43]
Net-Zero Targets & Policy	Net-zero emissions targets, climate-neutrality vs. carbon-neutrality, and abatement cost models.	[46, 47, 48]
GHG Protocol & Corporate Reporting	The Greenhouse Gas Protocol corporate standard and EU Corporate Sustainability Reporting Directive.	[49, 50]
Renewable Raw Materials	Benchmarking carbon emissions performance and using recycled materials in supply chains.	[51, 52]
Electric Logistics & Carbon Tax	Carbon emission reduction, pricing policies, and optimal carbon tax design for supply chains.	[53, 54]
Biomass & Factory Decarbonization	Biomass co-firing options and greening edge AI by harnessing carbon markets.	[55, 56]
Sustainable Industry Economics	Economics of zero-waste fashion and prescriptive analytics for supply chain resilience.	[58, 66]
Storage & Energy Efficiency	Net-zero economy research and lifecycle tracking of packaging return loops.	[59, 60]
Reverse Logistics & Sharing	Analytical models for economic and environmental benefits of resource-sharing schemes.	[62]
Supply Chain Leadership & AI	Supply chain leadership reviews and artificial intelligence for corporate carbon neutrality.	[63, 64]
Bibliometric Analysis of Carbon	Bibliometric analysis of carbon neutrality research hotspots and neural network inventory controllers.	[65]
Decarbonisation Decision Systems	Integrated evidence-based decision support systems for product supply chains.	[69]
Carbon Offsets & Materials	Carbon offsetting with eco-conscious consumers and perovskite material properties under pressure.	[70, 71]
Banking & Construction Automation	Digital transformation in banking and robotics/automation in construction management reviews.	[72, 73]
Technology Acceptance & Emissions	Factors affecting generative AI use in higher education and natural gas greenhouse gas emissions.	[74, 75]
Quantum Sensing & Groundwater	CogAT/ACT Aspire comparisons, cold-atom quantum gravimeters, and BGS hydrogeological reports.	[76, 77, 78]
Smart City Infrastructure	Advanced frameworks in smart city sustainable infrastructure and digital ledger integration.	[79]
Blockchain Revolution	Foundational principles of blockchain technology, Bitcoin, and decentralized ledgers.	[80, 86]
IoT Enablement & 6G Networks	Internet of things architectures, enabling technologies, and 6G wireless communication visions.	[82, 83, 84]

Section / Claim Topic	Specific Statement / Claim in Manuscript	Mapped Reference(s)
Tensor Networks & Edge AI	Universal variational quantum computation and tensor network methods for edge intelligence.	[85]
Decentralized Storage & Ethereum	IPFS content-addressed file systems and Ethereum secure decentralized transaction ledgers.	[87, 88]
IoT Smart Contracts	Blockchains and smart contracts for the internet of things and actuator automation.	[89, 93]
Lattice Cryptography & Signatures	Decade of lattice cryptography, RSA public-key cryptosystems, and Diffie-Hellman key exchange.	[90, 91, 94]
Zero-Knowledge Proofs & Szabo	Knowledge complexity of interactive proof systems and Nick Szabo's smart contract foundations.	[92, 93]
Lattice Learning with Errors (LWE)	LWE over rings, random linear codes, and practical Byzantine fault tolerance consensus.	[95, 96, 97]
Principal Component Analysis (PCA)	Mathematical formulation of principal component analysis in chemometrics.	[98]
Quantum Classifiers	Implementing distance-based classifiers on quantum computers.	[99]
Variational Quantum Algorithms	Comprehensive review of variational quantum algorithms in modern physics.	[100]

PRISMA Flow Diagram

