

Design, Implementation, and Environmental Effects of a Load-Balanced Smart Waste Management System Powered by Fog Computing in Iraq

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ABSTRACT: This paper designs and evaluates a load-balanced fog-computing architecture for smart waste management in Iraq. The study addresses the gap in context-specific evidence on how fog-layer task allocation affects latency-sensitive waste-monitoring services under constrained communication conditions. A three-tier IoT-fog-cloud model was implemented in iFogSim2 with 25 fog nodes distributed across five governorate clusters and 1,250-2,500 simulated IoT devices. Four strategies-Round Robin, Weighted Round Robin, Throttled, and Honey Bee-inspired allocation-were compared over 30 independent replications using latency, energy consumption, throughput, recovery time, and data loss. Throttled allocation achieved the strongest overall profile, reducing average latency by 34% compared with Round Robin under normal conditions ($p < 0.001$; Cohen's $d = 2.14$) and lowering energy use by approximately 18.5%. The findings indicate that dynamic, load-sensitive allocation is more suitable than static allocation for smart waste monitoring in Iraq, provided that minimum connectivity, device security, operator training, and institutional data governance are addressed.

Keywords: iFogSim2, Fog computing, Internet of Things (IoT), Smart waste management, Load balancing, Iraq, Environmental monitoring, Simulation



1. INTRODUCTION

The municipal solid waste management systems within Iraq need monitoring systems which will be able to perform effectively despite the presence of partial garbage collection, poor connectivity, lack of financial resources, and increased environmental degradation due to open dumping, leaching, landfill gases, and air pollution in the locality [1]. In this situation, the Internet of Things sensors will be effective in providing information about bin contents, vehicle tracking, and hazards, but cloud-based solutions alone cannot address urgent notifications.

Therefore, fog computing is used in this research as an intermediary level of computation between the edge devices and the cloud computing environment. Placing the processing capacity close to the bins, trucks, transfer stations, and chosen landfill sites will provide an opportunity for filtering, prioritization, and triggering emergency notifications locally before forwarding the selected information to the cloud environment [2].

The specific research gap is the absence of a structured, Iraq-oriented comparison of fog-layer load-balancing strategies for smart-waste services. Prior smart-waste studies frequently emphasize sensing, dashboards, routing, or cloud storage, whereas the operational consequences of assigning heterogeneous data tuples to constrained fog nodes have received limited comparative evaluation in the Iraqi context [3].

This paper responds to that gap by designing a three-tier IoT-fog-cloud architecture, modelling a five-governorate deployment scenario, comparing Round Robin, Weighted Round Robin, Throttled, and Honey Bee-inspired load balancing in iFogSim2, and interpreting the results together with deployment prerequisites related to connectivity, security, operator training, stakeholder coordination, and phased piloting [4].

The study is organized around three research questions: (RQ1) What fog-computing configuration is suitable for smart waste-management services in Iraq? (RQ2) Which load-balancing strategy provides the most favorable latency, energy, throughput, recovery, and data-loss profile under the simulated assumptions? (RQ3) What socio-technical requirements must be addressed before moving from simulation to a controlled municipal pilot?

2. Literature Review

2.1 Fog computing for distributed IoT services

Fog-computing studies show that placing computation, storage, and control closer to IoT devices can reduce end-to-end latency, decrease backhaul traffic, and support local response when links to centralized clouds are delayed or unstable [5]. For waste-management services, this means that overflow alarms, gas readings, tampering events, and vehicle-location messages can be pre-processed at the fog layer before non-urgent records are transmitted to the cloud [6].

2.2 IoT-enabled smart waste-management applications

IoT-enabled smart-waste applications commonly rely on ultrasonic sensors, weight sensors, GPS modules, environmental sensors, dashboards, and routing algorithms to detect fill levels, locate vehicles, and prioritize collection. These contributions are important, but they do not by themselves determine how computational tasks should be distributed when hundreds or thousands of devices generate simultaneous monitoring data [7].

2.3 Load balancing in fog architectures

Load balancing addresses this distribution problem by allocating incoming tuples according to node capacity, workload state, queue length, or adaptive behavior. Simple Round Robin is not aware of node diversity and any real-time traffic. Weighted Round Robin takes into account the relative computing power while the other two algorithms react to actual network conditions, which becomes crucial for timely notifications [8].

2.4 Synthesis and research gap

Consequently, the three premises suggested by the literature are that sensing through IoT is required for smart-waste to be visible; fog computing can be useful for processing, especially local and delay-sensitive processing; and load balancing will determine whether resources in the fog are effectively utilized. What remains unclear is how the various load balancing schemes will perform when applied in an Iraq-specific smart-waste context [9].

3. Iraq Waste Management Context

The context for waste management in Iraq includes high volumes of municipal waste, inconsistent waste collection, insufficient treatment facilities, unregulated disposal sites, and pollution due to open dumping [10]. The parameters of the context illustrated in Table 1 serve to drive the simulated scenario and calibrate workload intensity; they are not presented as measurements generated by the proposed system.

Table 1 Key contextual parameters used to motivate the Iraq smart-waste simulation scenario

Indicator	Value	Source / Basis	Year	Use in This Study
National MSW generation	11.2 ± 1.5 million tons/year	Ministry of Environment / JICA compilation [11]	2022	Scenario-scale calibration
Baghdad daily generation	8,500 ± 1,500 tons/day	UNDP / municipal reporting basis [12]	2024	Urban workload motivation
Per-capita generation	1.15 ± 0.25 kg/day	World Bank-style estimate range [13]	2023	Device-density assumption
Unregulated landfill sites	149 of 221 sites (67.4%)	JICA solid-waste study [14]	2022	Environmental monitoring priority
Estimated methane emissions	18,234 tons/year	IPCC Tier 1 calculation from landfill data [15],	2022	Environmental benefit indicator
Waste-to-energy potential	45–75 MW	Preliminary engineering scenario [16]	2024	Policy-planning context

Table 1 proves the necessity of the proposed intelligent waste surveillance system for Iraq [17]. The Waste to Energy conversion capacity was considered as an indicator for policy planning considering partial gas collection and generator efficiency, while simulations were restricted to only fog node performance, balancing, latency, energy consumption, recovery, and loss.

4. Fog Computing Architecture

The proposed system follows a three-tier IoT-fog-cloud architecture. The Edge layer consists of sensors for measuring fill level, weight, location, methane, volatile organic compound content, temperature, leachate potential, and tampering in bins, vehicles, transfer stations, and landfills. The Fog layer includes nodes of municipal or governorate scale that filter sensor data streams, classify critical events, perform load balancing, and send filtered information to the Cloud layer.

Such an architecture would allow making instant decisions for actions like sending out a waste pickup truck, altering routes due to reaching capacity, issuing warnings from elevated dangerous gas levels, or reacting to fire risk indicators. The ability to process time-sensitive events within the fog layer lowers reliance on constant, high-speed cloud connectivity that may be unreliable given the power and internet availability issues.

Ultrasonic sensors at the edge level monitor bin fullness, GPS sensors record vehicle movement, and environmental sensors record methane and certain pollutants at disposal sites. Data packets are sent to the nearest fog node via any means of available communication like Wi-Fi, 3G, 4G, LTE, etc. Choosing cost-effective devices is important because a real-life implementation in Iraq will involve deploying numerous such devices.

In the fog layer, data collected by sensors is filtered, prioritized, and allocated to processing nodes based on the evaluated load balancing approach. Data for regular observations is aggregated and sent to the cloud, whereas any emergency data such as overflows, tampering, increased methane concentration, or fire hazards is processed at the local level.

At the cloud tier, the system supports historical databases, environmental dashboards, waste-generation forecasting, geospatial planning, and circular-economy reporting. Cloud functions are therefore reserved for long-horizon analytics and policy support, while the fog layer handles short-horizon alerts and operational control [18].

5. Load-Balanced Fog Simulation and Evaluation Methodology

Design science modeling and simulation-based evaluation techniques have been used in the methodology. The artifact is a three-tier smart waste model, which uses simulation-based evaluation to compare four load balancing techniques in the allocation of waste monitoring streams to fog nodes. The Iraq context parameters are used to develop a realistic work load situation.

The simulated edge layer includes smart bins, vehicle-monitoring units, and selected disposal-site sensors. These devices generate fill-level, location, and environmental tuples. Urgent tuples are treated as latency-sensitive because delayed processing can affect overflow response, gas-risk escalation, or vehicle dispatch, whereas aggregated trend data is treated as latency-tolerant and suitable for cloud upload.

There are four methods considered for comparison under similar topology and workload conditions. Round Robin schedules tuples on a rotating basis and acts as a static baseline approach. The Weighted Round Robin approach uses the relative computing capacities of the fog nodes. Throttling algorithm selects the node which has the minimum load factor based on CPU usage, memory usage, and queue length [19].

The process of communicating between edge devices, fog nodes, and cloud services is carried out via Wi-Fi, 3G, 4G, LTE, and low-bandwidth networks. The usage of GIS is considered when implementing hotspot analysis and routing services, however, it is assumed that all Iraqi deployment locations do not possess equal communication capabilities.

iFogSim2 was selected for running the simulation as it allows modelling events discretely in applications based on IoT-fog-cloud, modular applications, tuple transfers, constraints on resources for devices, link latencies, and energy usage. This tool is suitable for the research aim of assessing the allocation strategies in the fog layer.

Environmental impacts that may potentially result from improved sensing and allocation are operational in nature as opposed to being direct impacts observed on the ground in the field. These include fewer trips to collect garbage, quicker identification of hazards, as well as better routing information among others.

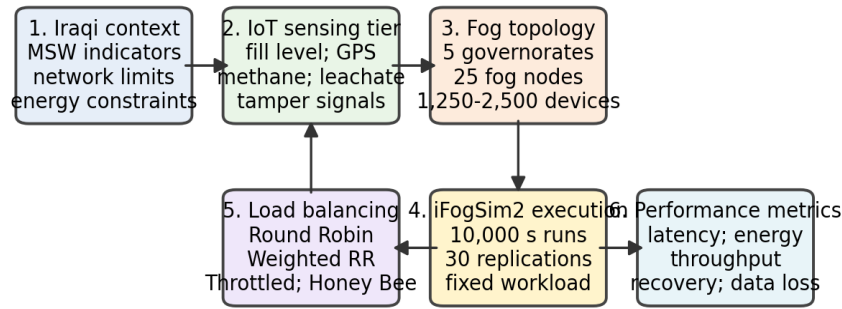
The process of design is divided into four steps namely; requirement gathering, system architecture, simulation configuration, and performance analysis. Requirement gathering was based on the situation in Iraq with respect to waste management and previous researches carried out with regard to IoT-fog. The system architecture involved allocation of roles to sensors, fog nodes, cloud, and security features. In simulation configuration, the parameters were fixed.

To ensure comparability, all algorithms were tested on the same topology, device population, tuple-generation intervals, link-delay ranges, bandwidth assumptions, and fog-node capacity distribution. Performance differences are therefore attributed to allocation logic rather than to changes in the experimental environment.

The three-tier architecture comprises ultrasonic sensors, weigh-in-motion sensors, GPS units, and environmental sensors used in bins, vehicles, and some selected locations for dumping garbage. The fog nodes carry out preliminary filtering and classification of tasks, and the cloud is responsible for historical storage and geospatial planning tasks.

Events related to emergencies, such as overflow, fire danger, chemical spill, and high methane levels, are then forwarded to the fog level for immediate analysis. All other non-emergency events are analyzed, combined, and uploaded to the cloud platform. The assumptions of security include encryption, authentication, tamper detection, and phased deployment.

Simulation Workflow and Evaluation Logic



The workflow separates contextual motivation from simulation evidence and makes the evaluation reproducible.

FIGURE 1 Revised high-resolution simulation workflow linking Iraqi waste-management requirements, fog topology, load-balancing algorithms, iFogSim2 execution, and evaluation metrics

Figure 1 summarizes the revised simulation workflow. It clarifies the sequence from Iraq-specific contextual assumptions to IoT sensing, fog topology, load-balancing configuration, iFogSim2 execution, and performance assessment, making the experimental logic more transparent and reproducible.

Simulation time was set at 10,000 seconds which is roughly 2.78 hours. There were 25 fog nodes in total, with five nodes allocated per governorate cluster. Each node had between 50-100 IoT devices, resulting in between 1,250-2,500 simulated devices. Fog-node capacity ranged from 2,000 to 4,000 MIPS with 4 GB RAM, while the cloud data center was configured with 100,000 MIPS and 64 GB RAM. Local-area delays ranged from 2 to 10 ms, wide-area delays ranged from 50 to 300 ms, and bandwidth ranged from 256 kbps to 2 Mbps.

Sensor tuples were generated every 5-30 seconds, with packet sizes of 256-512 bytes. The processing module used a selectivity of 0.3 and required 10-50 ms per tuple. The analytics module was considered latency-tolerant beyond five seconds. Environmental and waste-generation assumptions were used only to set workload intensity; the reported performance values are simulation results.

Five metrics were used for evaluation: end-to-end latency, energy consumption, throughput, recovery time after node failure, and data-loss rate. Alert tuples with latency below 500 ms were considered suitable for urgent operational response. Thirty independent replications were conducted for each algorithm and compared against the Round Robin baseline.

Algorithm 1. Reproducible simulation and comparison procedure

Inputs: five-governorate fog topology; 25 fog nodes; 1,250-2,500 IoT devices; tuple-generation interval of 5-30 seconds; packet size of 256-512 bytes; local delay of 2-10 ms; wide-area delay of 50-300 ms; and network bandwidth of 256 kbps to 2 Mbps.

Step 1: Initialize the random seed and generate the five-governorate topology with fixed node-capacity ranges.

Step 2: Configure the four load-balancing strategies: Round Robin, Weighted Round Robin, Throttled ($\alpha = 0.4$, $\beta = 0.3$, $\gamma = 0.3$), and Honey Bee-inspired allocation.

Step 3: Run 30 independent replications per algorithm using identical workload, tuple size, delay ranges, and fog-node capacity assumptions.

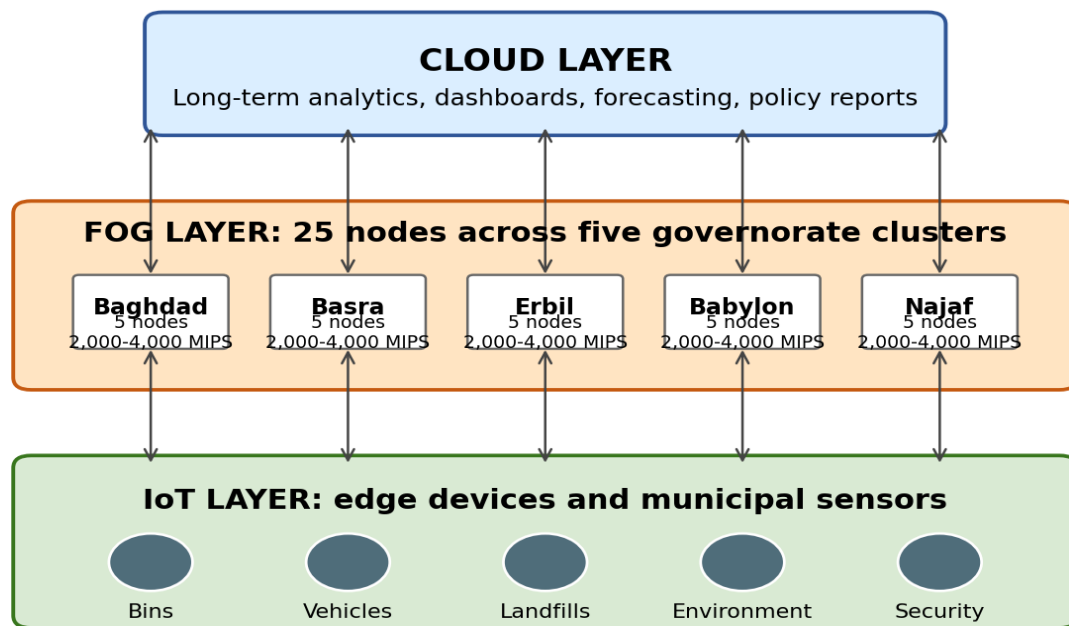
Step 4: Collect latency, throughput, energy use, recovery time, and data-loss rates for every replication.

Step 5: Compare each strategy with Round Robin using statistical significance, effect size, and implementation constraints before drawing conclusions.

6. Security Architecture

The security architecture defines how the proposed system should be deployed securely rather than treating security as an optional add-on. It includes device authentication, encrypted communication, tamper detection, access control, and auditable environmental-event records. Mutual TLS 1.3 may secure sensor-fog-cloud communication, device-level signatures may protect tuple integrity, and permissioned audit mechanisms may be used only where institutional governance and node availability are sufficient.

Fog Computing Architecture for Iraq Waste Management



Fog performs filtering, prioritisation, local alerts, and load balancing; cloud stores historical and policy data.

FIGURE 2 Revised high-resolution three-tier fog-computing architecture for smart waste management in Iraq

Table 2 Security threats, safeguards, implementation requirements, and deployment constraints

Threat	Mitigation	Implementation	Deployment Constraint
Spoofing	Mutual TLS 1.3	X.509 certs with 90-day validity, automated renewal via ACME where possible	Requires reliable certificate management and renewal procedures
Tampering	Tamper-evident audit trail	Permissioned audit ledger, such as Hyperledger Fabric, where governance and ordering-node availability are feasible	Requires adequate node availability, access governance, and maintenance of audit infrastructure
Repudiation	Digital signatures	All sensor data signed with Ed25519 at device level	Requires tamper-resistant device handling and periodic key rotation
Information Disclosure	AES-256-GCM	Keys derived from TPM 2.0 where available; software TPM fallback	Depends on secure key storage; software fallback should be limited to pilots
Denial of Service	Rate limiting and controlled cloud fallback	Per-node request limits; failover to an approved regional cloud or national data center	Requires approved hosting, failover policy, and service-level monitoring
Elevation of Privilege	Role-based access control and least privilege	Defined roles for federal administrators, governorate operators, field collectors, and auditors	Requires agreed inter-agency role governance and periodic access review

Implementation prerequisites include secure device-identity management, certificate issuance and renewal, key management, operator training, access-review procedures, and clear assignment of data-governance responsibility. Because municipalities differ in readiness, deployment should begin with a controlled pilot and expand through standard operating procedures [20].

7. Socio-Technical Feasibility

Feasibility from a socio-technical perspective is considered so that evidence from the simulation can be related to implementation conditions. For environmental agencies, it is necessary to have accurate data; for cities, there should be dashboards and routing capabilities; for companies offering such services, there should be clear procurement guidelines and performance agreements; and for citizens, information dissemination channels are needed.

The informal sector should not be seen as an impediment to progress but as one of the affected stakeholders. An intelligent waste program might change the way recyclable material is accessed; therefore, the transition should have mechanisms put in place such as sorters' pay, micro-franchising of recycling, and better safety awareness training.

While the simulation confirms the technical feasibility of the project, its actual success hinges on coordination among actors at national, regional, and municipal levels. There needs to be an agreement on procurement, data management, maintenance, and alarm response.

Also important is financial and administrative preparedness. The use of smart-waste technology requires regular funding for sensors, fog nodes, connectivity, cybersecurity, device replacement, and training. It will be better to link the system with city service contracts with performance measures, once the pilot phase has been completed.

Table 3 Stakeholder feasibility matrix for phased smart-waste implementation

Stakeholder	Power	Interest	Engagement Strategy	Implementation Barrier
Federal Ministry of Environment	High	High	Co-design; data ownership	Budget approval cycles; inter-agency coordination
Baghdad Municipality	High	Medium	Pilot-site provision; dashboard use	Maintenance priorities; limited technical staffing
KRG/Erbil	Medium	High	Federated architecture	Data-sharing protocols; system interoperability
Informal waste workers	Low	High	Training; paid sorting and recycling roles	Livelihood transition risk without inclusion
International NGOs	Medium	Medium	Funding and technical assistance	Security and donor-coordination requirements
Local communities	Low	High	Public dashboards; complaint channels	Variable digital literacy; icon-based interface needed

Human-capacity requirements include dashboard operation, basic troubleshooting, device maintenance, data-quality checks, privacy compliance, and emergency-response procedures. Where digital literacy varies, interfaces should use icon-based and voice-supported alerts in addition to conventional dashboards.

8. Implementation Considerations and Future Work

This gives evidence to support the feasibility of the architecture and allocation logic in a simulated environment. Controlled field pilot testing needs to be undertaken at the next phase of validation including network outage, power cut-off, sensor drift, vandalism, maintenance latency, municipal reaction, and operator usability issues.

Future research should identify suitable urban and peri-urban locations, measure actual packet loss distribution patterns, incorporate GIS routing algorithms, assess operator acceptance, and analyze hybrid approaches using both Throttled allocation and load forecasting.

Another area of potential study would involve the use of light-weight edge intelligence to conduct image classification and anomaly detection. These services should be offered after validation of the fog environment, its connectivity, security, and maintenance processes.

9. Results and discussion

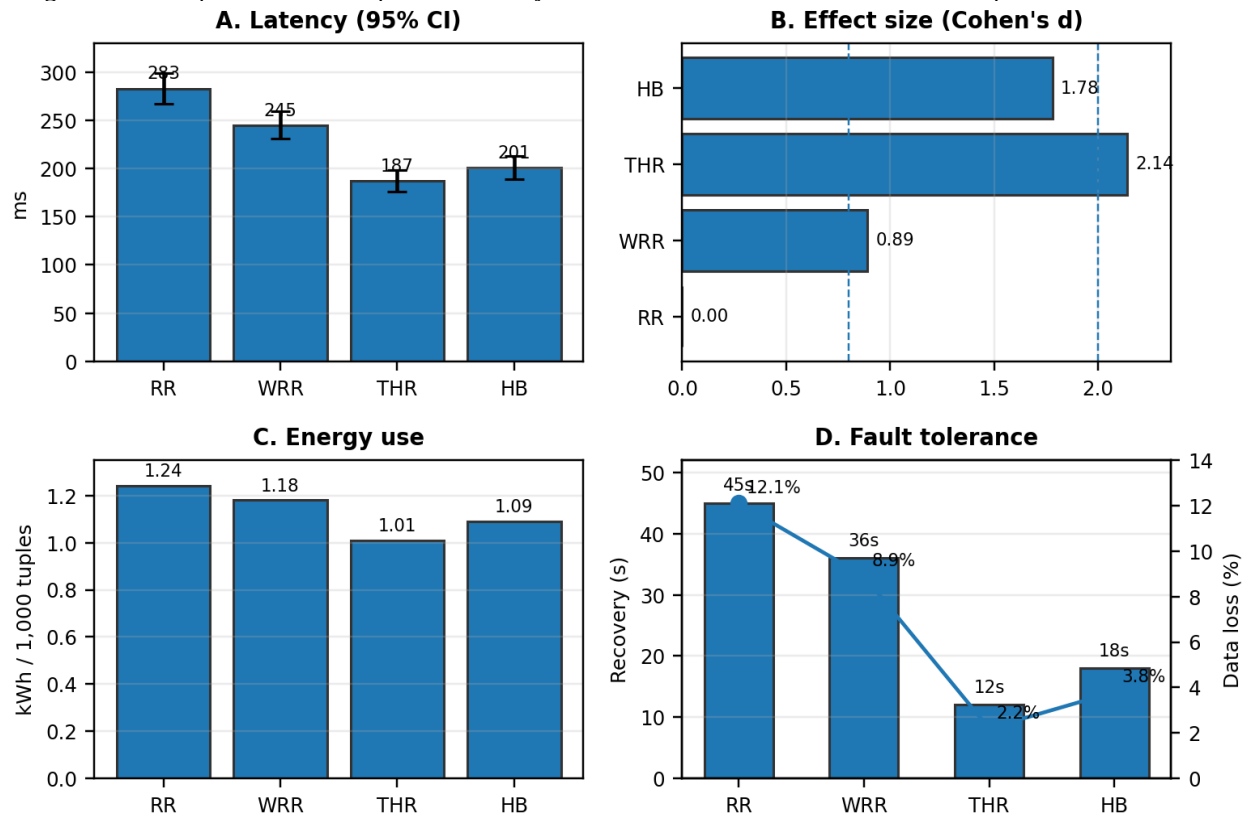
Under normal operating conditions, dynamic strategies reduced latency compared with the static Round Robin baseline. Mean latency was 283 ms for Round Robin, 245 ms for Weighted Round Robin, 187 ms for Throttled, and 201 ms for Honey Bee-inspired allocation. This indicates that capacity-aware and load-aware allocation improves responsiveness in a fog-based waste-management system.

The superior latency result of Throttled allocation is explained by its use of a live load index based on CPU utilization, memory utilization, and queue length. Honey Bee-inspired allocation also improved performance, but its decentralized adaptation produced slightly higher latency than Throttled under the tested workload.

Energy utilization followed a similar trend. Round Robin utilized 1.24 kWh for processing 1,000 data units, Weighted Round Robin utilized 1.18 kWh, Throttled utilized 1.01 kWh, and the allocation method inspired by Honey Bees used 1.09 kWh. The lesser consumption of energy during dynamic resource allocation can be attributed to lesser congestion and optimal task distribution in fog nodes.

Resilience was measured when 20% of fog nodes were disabled after 5,000 seconds. The Round Robin strategy had a slow recovery rate since it kept allocating resources without being fully aware of any faulty nodes. The Weighted Round Robin had better performance in terms of recovery since capacity allocation was involved. Meanwhile, Throttled and Honey Bee strategies had faster recovery rates.

Figure 4 shows that load balancing and connectivity must be considered together. With increase in bandwidth, all methods performed better, but the method with the least latency was Throttled. With highly restricted bandwidth, there were no clear algorithmic advantages since the network latency was greater than the processing latency. Therefore, load balancing makes an improvement in response time only if there is some minimal communication possible.



Abbreviations: RR = Round Robin; WRR = Weighted Round Robin; THR = Throttled; HB = Honey Bee-inspired.

FIGURE 3 Revised high-resolution comparison of latency, effect size, energy consumption, and fault-tolerance behaviour for the tested load-balancing algorithms

Table 4 Comparative latency performance and effect-size estimates for the tested load-balancing algorithms

Algorithm	Mean Latency (ms)	95% CI	Std Dev	Effect Size (d)
Round Robin	283	[267, 299]	45	—
Weighted RR	245	[231, 259]	39	0.89 (large)
Throttled	187	[176, 198]	34	2.14 (very large)
Honey Bee	201	[189, 213]	36	1.78 (large)

Statistical comparisons against Round Robin indicate significant performance differences across the evaluated runs ($p < 0.001$), with large or very large effect sizes for the dynamic load-balancing strategies.

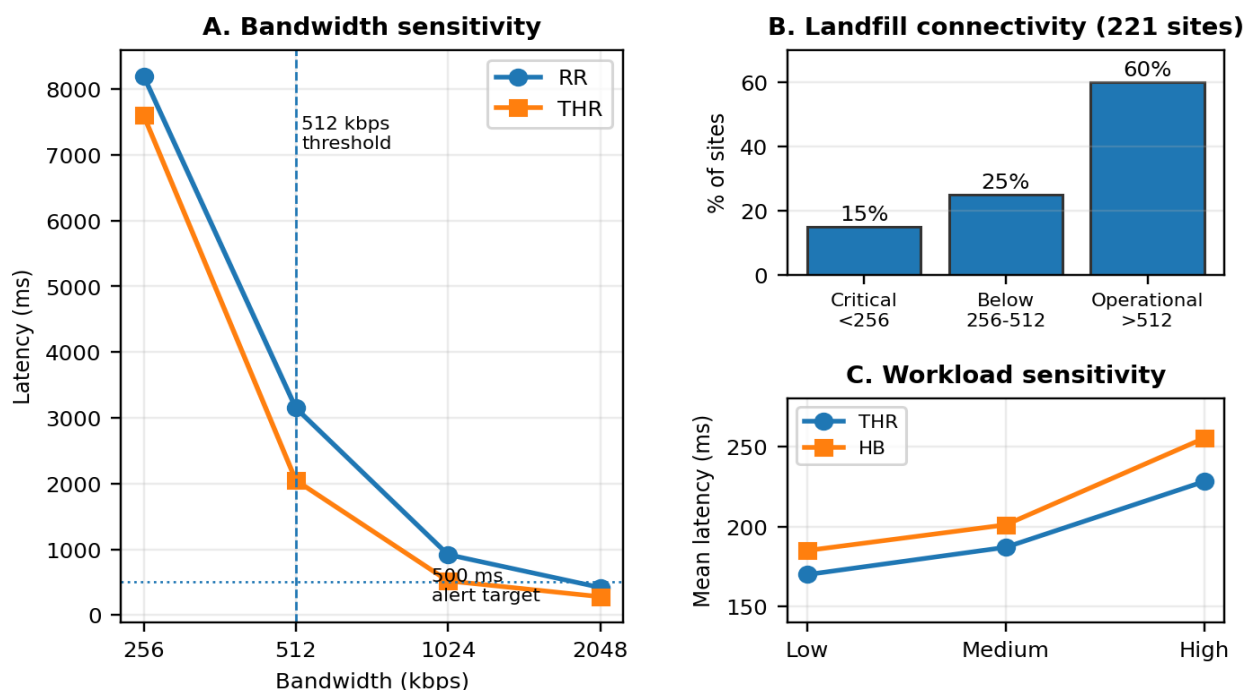


FIGURE 4 Revised high-resolution infrastructure-sensitivity analysis showing bandwidth thresholds, landfill-connectivity status, and workload sensitivity

10. Conclusion

In this paper, an efficient load balancing architecture for intelligent waste management using Fog Computing in Iraq was developed and analyzed. The architecture uses IoT, fog computing nodes at governorate levels, Cloud services, secure communication channels, and GIS-based planning to ensure immediate alert handling is done locally and past data are preserved for future analysis. In the iFogSim2 simulation, dynamic allocation has performed better than static Round Robin given the considered assumptions. Throttled allocation worked best since task assignments were made depending on real-time status of the fog nodes while Honey Bee inspired allocation was significantly better than static allocation.

The importance of the environment from the architectural perspective can be seen indirectly but very relevantly – the ability to react more promptly on overflow, less wasted trips on unnecessary pickups, quicker identification of hazardous sites, and more useful information for recycling/composting/methane management.

To scale the system in Iraq, there must be minimum connectivity, stable electricity, maintainable systems, cybersecurity preparation, skilled workers, and governance around data ownership. For this, municipal pilots are recommended before scaling up.

In conclusion, the most suitable tested approach for implementing the suggested smart-waste management scheme in Iraq via fog computing is Throttled Load Balancing because it offers the most robust combination of latency, energy efficiency, and reliability. The future research agenda could include piloting of the system, exploration of other load balancing approaches, analysis of packet losses, and cost-benefit analysis of the solution.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest

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