Leveraging Surplus Android Phones in India: Scalable Use Cases in Edge Computing, Digital Health, and Smart Infrastructure

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Abstract— **India's rapid smartphone adoption and short device replacement cycles have led to a significant accumulation of surplus Android phones—contributing to the over 1 million tonnes of e-waste generated annually in the country [2]. These discarded devices, despite having adequate processing, sensing, and communication capabilities, are frequently retired due to superficial hardware issues or software obsolescence.**

This paper presents a theoretical framework to model the repurposing of surplus Android smartphones as a cost-effective and scalable layer of decentralized digital infrastructure. We argue that these devices can be re-integrated into public systems to enable edge computing capabilities for various social impact domains, including healthcare, education, environmental monitoring, and smart agriculture.

To support this proposition, we introduce three core constructs: techno-social innovation, describing the co-evolution of community practices and technology; frugal digital infrastructure, which emphasizes low-cost, locally adaptable digital systems; and decentralized edge ecology, a conceptual model for loosely coupled edge devices operating collaboratively in resource-constrained environments.

We propose a taxonomy of reuse applications and detail a prototype deployment focused on air quality monitoring using refurbished Android devices. Our findings illustrate how surplus smartphones can contribute to sustainable ICT infrastructure, digital inclusion, and e-waste mitigation efforts. This research extends the discourse on circular technology economies and offers actionable insights for low-resource settings in the Global South.

Keywords— Android reuse, edge computing, frugal innovation, e-waste mitigation, mobile health, education technology, environmental sensing, digital inclusion, sustainable ICT.

I. INTRODUCTION

India is one of the fastest-growing smartphone markets globally, with over 800 million mobile internet users and an annual shipment of more than 150 million smartphones [1]. However, the rapid pace of device replacement—averaging just 2.5 years per phone—has resulted in an escalating volume of surplus and discarded devices [1], [2]. Many of these phones are retired due to perceived obsolescence, minor hardware defects, or discontinued software support, despite retaining substantial computational, sensing, and connectivity capabilities.

This surplus presents both a challenge and an opportunity. On one hand, improper disposal of smartphones contributes to the burgeoning e-waste problem, which poses environmental and health hazards due to the presence of toxic materials [2]. On the other hand, these devices can be strategically repurposed into a decentralized computing fabric capable of supporting low-cost, distributed digital services in areas such as healthcare, education, agriculture, and environmental monitoring.

This paper proposes that surplus Android smartphones can serve as a frugal, techno-social innovation—a locally adaptable, low-cost solution that leverages both technological potential and community participation [3]. By forming a decentralized edge ecology, these devices can act as autonomous or semi-autonomous agents performing sensing, inference, communication, and coordination tasks in diverse, often resource-constrained settings.

Our central hypothesis is that surplus Android phones, when equipped with secure and purpose-built software stacks, can be transformed into modular components of India's digital public infrastructure. This infrastructure can complement national initiatives such as Digital India, Smart Cities, Ayushman Bharat, and the National Education Policy (NEP) by extending digital access in a cost-effective and environmentally sustainable manner [4], [5].

To support this vision, we present a layered framework that evaluates the reuse of smartphones along three dimensions:

- **Technological feasibility:** Can the device be repurposed reliably for sensing, inference, and communication?
- **Societal relevance:** Does the deployment address genuine local needs across health, education, or environment?
- **Deployment scalability:** Can it be adapted across rural, urban, and underserved contexts with minimal infrastructure investment?

While global initiatives such as Right to Repair in Europe and device reuse pilots in Sub-Saharan Africa have made important strides, many faced challenges due to fragmented ecosystems, limited public integration, or closed-source platforms. By contrast, India's combination of a robust Android developer ecosystem, active public digital programs, and device surplus offers a unique opportunity for scalable, policy-aligned reuse.

By synthesizing concepts from ICT4D (Information and Communication Technology for Development), frugal innovation, and circular economy theory, we aim to contribute a conceptual and practical model that informs policy, system design, and future research.

II. BACKGROUND AND MOTIVATION

The reuse of surplus Android smartphones intersects with several macro trends: the accelerated lifecycle of consumer electronics, the open nature of the Android platform, the growing need for frugal digital infrastructure, and alignment with India’s national development priorities. This section outlines the foundational context for our proposed framework.

A. Smartphone Lifecycle in India

India’s smartphone market is characterized by frequent product refreshes, aspirational consumer behavior, and aggressive marketing. As a result, devices are typically replaced every 2.5 years on average [1]. Many of these phones are retired prematurely due to outdated software, superficial damage (e.g., cracked screens), or unsupported components—despite being functionally viable [2].

While trade-in and recycling programs exist, many devices fall outside formal reuse ecosystems and contribute to India's rising e-waste footprint, which exceeded 1 million tonnes in 2023 [2].

B. Advantages of the Android Platform

Android’s open-source foundation makes it particularly well-suited for repurposing initiatives. Developers can utilize the Android Open Source Project (AOSP) or community-maintained firmware such as LineageOS to create lightweight, task-specific builds that strip away unnecessary services and enhance security [6]. These systems can support a range of I/O interfaces—USB OTG, Bluetooth, Wi-Fi—and run edge inference models using TensorFlow Lite [7].

Unlike closed mobile ecosystems, Android’s modularity and vast installed base enable local customization and cost-effective scaling.

C. Alignment with National Development Agendas

India’s flagship digital initiatives—Digital India, Smart Cities Mission, Ayushman Bharat, and National Education Policy (NEP)—emphasize inclusive digital access and last-mile connectivity [4], [5]. However, these programs often face bottlenecks in rural and peri-urban areas where infrastructure is lacking. Refurbished smartphones offer a plug-and-play layer of edge intelligence to extend public services across education, healthcare, and environmental domains.

While global efforts such as Europe’s Right to Repair movement and Sub-Saharan reuse initiatives have advanced the reuse agenda, they often lack integration with public digital programs or face fragmentation in hardware/software ecosystems. India’s combination of open platforms, abundant surplus devices, and mission-driven digital goals creates a distinctive opportunity to systematize reuse.

D. Frugal Digital Infrastructure

Frugal innovation emphasizes doing more with less—developing context-sensitive solutions using minimal resources [3]. We extend this idea into frugal digital infrastructure, where low-cost, locally sourced digital components (e.g., discarded smartphones) form reliable ICT systems. These infrastructures operate within tight power, bandwidth, and maintenance constraints, making them ideal for resource-constrained settings.

E. Techno-Social Innovation

The concept of techno-social innovation highlights the co-evolution of technology and community practices to meet social needs [8]. In our model, smartphones are not just technical nodes but vehicles for participatory innovation, with local stakeholders (teachers, health workers, citizens) contributing to design, deployment, and maintenance.

F. Decentralized Edge Ecology

We introduce the notion of a decentralized edge ecology: a distributed mesh of refurbished smartphones operating collaboratively or autonomously, often in offline or low-connectivity environments. These devices support localized sensing, inference, and decision-making, reducing dependency on cloud infrastructure.

G. Circular Technology Economy

Inspired by circular economy principles, this approach encourages closed-loop lifecycles—reprogramming and reusing devices multiple times before disposal [2], [9]. This not only reduces e-waste but aligns with India’s E-Waste Management Rules, national sustainability targets, and SDG 12 (Responsible Consumption and Production).

III. CATEGORIZED USE CASES

This section outlines five key domains where surplus Android smartphones can be repurposed as edge computing nodes, sensing platforms, or digital service enablers. Each use case demonstrates real-world feasibility and alignment with national development goals. These categories serve as a taxonomy of frugal reuse applications in low-resource settings.

A. Healthcare and Diagnostics

India faces a persistent shortage of healthcare personnel and diagnostic infrastructure, especially in rural areas. Repurposed smartphones can support mobile health (mHealth) and community health delivery through edge computing and sensor integration.

- **Mobile Diagnostics:** Built-in cameras and microphones can enable vision tests, hearing screening, and respiratory analysis using mobile apps [10], [11].
- **On-Device AI Screening:** TensorFlow Lite models can detect cough anomalies, skin lesions, or retinal signs offline [7], [12].
- **Field Surveys:** Health workers can use offline-capable survey tools to collect maternal, infant, or infectious disease data [11].
- **Maternal Health Monitoring:** Devices paired with Bluetooth-enabled wearables can track vitals during high-risk pregnancies [13].
- **Post-Treatment Adherence:** Reminders, medication trackers, and follow-up support apps enhance continuity of care.

B. Smart Agriculture

India's agricultural productivity is constrained by information gaps and limited access to precision tools. Repurposed phones can serve as decision support hubs for farmers.

- **Visual Crop Diagnosis:** Farmers photograph plant leaves; on-device CNN models detect disease or nutrient deficiencies [14].
- **Hyperlocal Alerts:** Weather, irrigation, or pest alerts can be shared over BLE mesh networks or SMS gateways [15].
- **Irrigation Automation:** Phones interface with soil moisture sensors and control pumps via relays, improving water use [16].
- **Livestock Tracking:** BLE tags on cattle transmit vitals and location to smartphones for herd management.
- **Soil Health Logging:** Sensors transmit pH, salinity, and moisture data for storage and analysis via mobile gateway nodes.

C. Air Quality Monitoring

Urban India suffers from high air pollution levels, but certified sensor networks are expensive and limited in reach. Repurposed phones can act as local AQI monitors when paired with affordable sensors.

- **Sensor Integration:** Devices connect to PM2.5/CO_2 sensors over USB OTG or BLE and display real-time AQI values [17].
- **Crowdsourced Microgrids:** Smartphones installed on rooftops, streetlights, or buses provide spatially distributed AQI data [18].
- **Edge Pre-Processing:** Devices filter and compress data locally before uploading, reducing network strain.
- **Citizen Science:** Local communities and schools use dashboards to interpret data and raise awareness.
- **STEM Curriculum Integration:** Devices support hands-on education in environmental monitoring and sustainability.

D. Education and Offline Learning

Rural schools often lack sufficient digital infrastructure to support NEP-aligned content. Repurposed devices offer offline, localized digital learning platforms.

- **Kiosk-Mode Learning:** Android phones can be locked to run education apps, enabling distraction-free content access [5].
- **Wi-Fi Direct Peer Learning:** Devices share educational material (PDFs, videos) peer-to-peer, even without the internet.
- **Teacher Assistance:** Phones function as smart teaching aids, providing quizzes, games, and translation tools [19].
- **Automated Grading:** OCR apps scan handwritten tests and calculate scores in real-time.
- **Digital Libraries:** Community kiosks with repurposed phones act as e-book and video access points in rural centers.

E. Smart Urban Infrastructure

Urban spaces often lack sufficient instrumentation for city operations. Repurposed smartphones can fill this gap as deployable edge nodes.

- **Traffic Monitoring:** Cameras on phones mounted near intersections can analyze traffic patterns using local video analytics [20].
- **Noise Mapping:** Microphones record ambient noise for crowd detection, noise pollution heatmaps, or nightlife regulation [21].
- **Civic Reporting:** Geo-tagged reports for broken infrastructure (potholes, lights) are submitted via mobile apps.
- **Leak Detection:** Acoustic data can identify plumbing or water pipeline leaks via audio anomaly detection.
- **Crowd Estimation:** Public spaces like stations or parks use phones for real-time footfall analysis using computer vision.

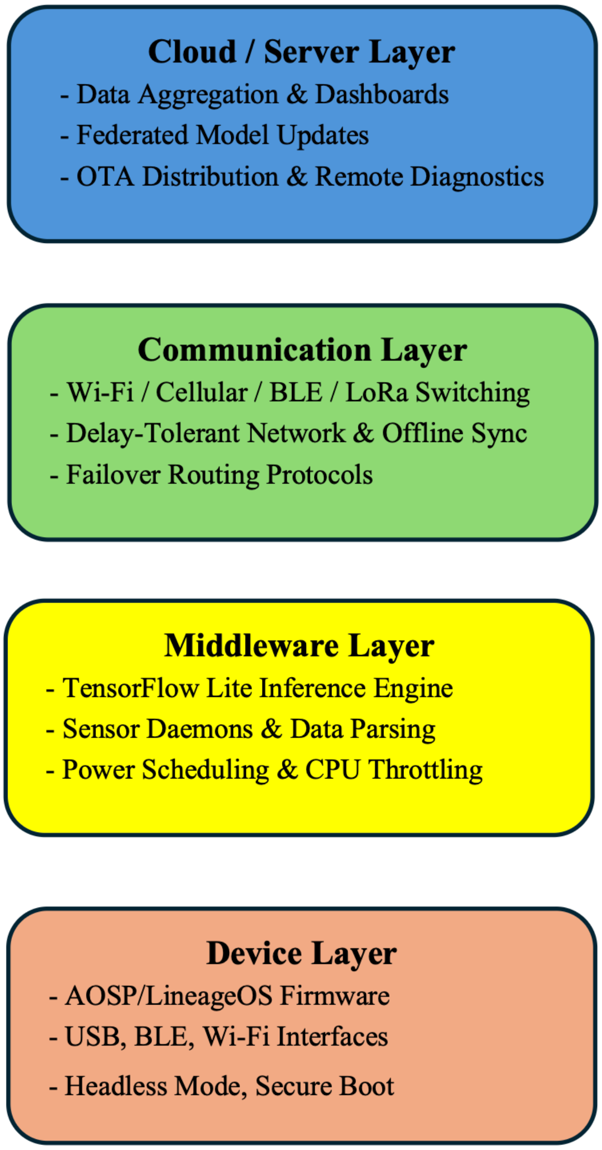
IV. SYSTEM ARCHITECTURE AND DEPLOYMENT

To enable practical reuse of Android smartphones for decentralized sensing and computation, we propose a four-layer system architecture. This layered approach supports modular design, scalable deployment, and resilience to environmental constraints such as power, connectivity, and hardware variability.

A. Device Layer

At the lowest level, surplus Android smartphones are configured as hardware nodes capable of sensing, inference, and control.

- **Operating System**: Devices run custom AOSP or LineageOS builds to strip non-essential services, minimize resource use, and enhance security [6].
- **Sensor Interfaces**: USB OTG, Bluetooth Low Energy (BLE), and Wi-Fi modules are used to interface with external sensors (e.g., PM2.5, soil moisture, BLE beacons).
- **Ruggedization**: Devices are enclosed in weather-resistant casings and powered using solar kits or power banks to support outdoor and semi-permanent installations.
- **Headless Operation**: Damaged displays are bypassed using ADB-based remote access or "kiosk mode" operation with locked-down launcher environments.



B. Middleware Layer

This layer hosts the logic for local computation, power optimization, and modular device control.

- **Edge Inference Engine**: On-device TensorFlow Lite models enable real-time decision-making (e.g., air quality classification, disease detection) without constant cloud access [7].
- **Sensor Daemons**: Lightweight applications continuously interface with attached sensors, parse incoming data, and cache relevant observations.
- **Power Scheduling Modules**: Tasks are scheduled during optimal power availability windows, with support for batching, sensor polling intervals, and CPU scaling.
- **Remote Management**: Devices are remotely diagnosable using ADB-over-network tunnels or WebUSB-based diagnostics tools, allowing firmware updates and log retrieval.

C. Communication Layer

Communication strategies are designed for resilience in low-connectivity environments.

- **Hybrid Network Stack**: Devices switch between Wi-Fi, cellular, BLE, and optionally LoRa or Zigbee based on availability and energy cost.
- **Delay-Tolerant Networking**: Data is buffered locally and uploaded in bursts when network connectivity is detected, reducing bandwidth usage.
- **Offline Sync Modes**: Peer-to-peer data exchange via Wi-Fi Direct or BLE mesh supports collaborative data sharing in disconnected environments [15].
- **Failover Protocols**: Redundant paths and retry mechanisms are employed to ensure eventual data delivery in unreliable networks.

D. Cloud/Server Layer (Optional)

While local edge processing is emphasized, cloud infrastructure can complement the architecture by providing visibility, coordination, and learning enhancements.

- **Data Aggregation**: Centralized servers collect and visualize data from devices for government dashboards, research, or citizen science platforms [18].
- **Federated Learning Support**: Model updates can be improved using privacy-preserving federated learning techniques, where models are trained locally and only gradients are uploaded [22].
- **Model Distribution**: Lightweight model updates and app configurations are distributed to devices via over-the-air (OTA) delta payloads, minimizing data consumption.

V. PROTOTYE INITIATION AS VALIDATION

To demonstrate the feasibility and applicability of the proposed framework, we present a prototype deployment focused on air quality monitoring in urban India. This instantiation acts as a **boundary object**—a tangible representation of the theoretical constructs described in previous sections, particularly the edge ecology and frugal infrastructure paradigms.

A. Deployment Overview

The pilot was conducted in the North Delhi region using five refurbished Android smartphones paired with low-cost particulate matter (PM2.5) sensors via USB-OTG. Devices were mounted on rooftops of residential and institutional buildings and powered using off-the-shelf solar kits and power banks.

Each phone ran a custom AOSP build stripped of background services to conserve power. A minimal Android app performed the following tasks:

- Periodic data acquisition from the PM2.5 sensor every 15 minutes.
- On-device filtering and smoothing of readings using a sliding average.

- AQI classification using a TensorFlow Lite model trained on Indian pollution datasets.
- Data caching and upload to a centralized server once per day using Wi-Fi or 2G fallback.
- The sensor-phone pairs were placed to represent different environmental contexts: high-traffic junction, residential block, park area, school rooftop, and industrial border.

B. Insights and Takeaways

This small-scale validation confirmed the following:

- **Edge Devices in Resource-Constrained Settings** Refurbished Android phones functioned reliably for over three months, demonstrating the viability of using such devices as standalone, ruggedized edge computing units.
- **Circular Reuse Models Are Technically Feasible** Devices considered e-waste were effectively reprogrammed and deployed as long-term sensing agents with minimal intervention.
- **Citizen Engagement and Local Co-Design** Residents and students from nearby schools participated in understanding AQI data through app-based dashboards, validating the techno-social innovation model. This participatory design also helped identify usability improvements.
- **Policy-Relevant Data Streams** AQI maps generated from the prototype were shared with municipal bodies, showing the utility of such microgrids in supplementing formal air monitoring systems.
- This prototype, though limited in scale, substantiates the potential for repurposed Android phones to serve as foundational blocks in decentralized and frugal digital ecosystems.

VI. CHALLENGES AND MITIGATION

While repurposing surplus Android smartphones offers significant potential for scalable and sustainable ICT deployments, it also introduces several technical, operational, and ethical challenges. This section outlines major issues and proposes corresponding mitigation strategies.

A. Hardware Degradation

Many surplus smartphones suffer from partial hardware failures, including degraded batteries, cracked screens, and damaged USB ports.

- **Battery Wear**: Devices were powered using external power banks or direct solar kits to bypass the need for internal batteries.
- **Screen Damage**: Headless operation was enabled via kiosk mode or remote ADB control, eliminating the need for physical UI [6].
- **Port Failures**: When USB ports were non-functional, Bluetooth sensors were employed as an alternative communication interface [15].

These adaptations allowed hardware-impaired phones to be reused effectively, thereby extending device lifecycles.

B. Software Compatibility and Security

Android's fragmentation presents compatibility issues across devices and versions. Additionally, many devices are vulnerable due to outdated software and unpatched security flaws.

- **OS Fragmentation**: Minimal, uniform OS builds (e.g., LineageOS) were used to standardize behavior across diverse hardware [6].
- **Security Hardening**: Devices were flashed with locked bootloaders and signed images to minimize tampering risks [20].
- **API Deprecation**: Abstraction wrappers were implemented to support legacy APIs and maintain cross-version compatibility.

By isolating non-essential services and locking down firmware, the attack surface was reduced while enabling controlled updates.

C. Data Privacy and Ethical Compliance

Repurposed devices, especially in healthcare or education settings, often handle sensitive user data.

- **Encryption**: All field-collected data was encrypted at rest and in transit using TLS 1.3 and AES-256 [20].
- **Consent Management**: Applications included opt-in screens and user consent workflows aligned with GDPR and India's Personal Data Protection Bill [21].
- **Data Minimization**: Only necessary data was captured, and personally identifiable information (PII) was anonymized at the edge before upload.

These practices ensured compliance with international data ethics norms and mitigated the risk of misuse.

D. Standardization and Interoperability

One of the biggest barriers to scale is the lack of standardized frameworks for device qualification, app deployment, and sensor integration.

- **Reference Designs**: A catalog of validated device models with known sensor interfaces and OS compatibility was maintained.
- **Open APIs**: Middleware components used open-source sensor abstraction libraries and data formats (e.g., JSON over MQTT/HTTP).
- **Deployment Templates**: Installation scripts, diagnostic utilities, and OTA management tools were bundled into reproducible kits.

By creating interoperable standards, the ecosystem can scale across geographies, use cases, and institutions with minimal customization.

E. Counterfeit and Non-Standard Devices

A field challenge was the presence of counterfeit or carrier-locked phones with inconsistent hardware/software behavior.

- **Mitigation:** Devices were screened pre-deployment using checksum validation, bootloader inspection, and port testing. Counterfeit-prone models were excluded from the reference design set.

VII. POLICY IMPLICATION AND DEPLOYMENT STRATEGY

To scale the reuse of surplus Android smartphones as a national digital infrastructure layer, a clear policy roadmap and deployment strategy must be established. This section outlines actionable policy recommendations and a phased deployment plan, aligned with India's existing digital and sustainability missions.

A. Policy Recommendations

We propose a three-pillar policy framework to promote the reuse of smartphones within public systems.

1) Decentralization Incentives

State and local governments should be encouraged to adopt **ward-level or school-based deployments** of refurbished devices. Localized control improves responsiveness and ensures alignment with specific community needs. Incentivizing these pilots through financial support, recognition, or capacity-building grants can catalyze grassroots adoption.

2) Circular Technology Mandates

In line with India’s E-Waste Management Rules [2], procurement policies can be amended to mandate the reuse of surplus government-owned devices for internal digital transformation projects. Ministries and public-sector undertakings (PSUs) can designate a percentage of their IT refresh budgets for refurbishment initiatives.

3) Open Innovation Grants

To build a sustainable ecosystem around repurposed infrastructure, open innovation grants should support:

- Development of free and open-source software (FOSS) for Android reuse.
- Standardized firmware, diagnostic tools, and hardware APIs.
- Collaborations between local integrators, academic institutions, and civic technology organizations.

Such grants would empower grassroots developers and reduce dependency on proprietary platforms.

B. Deployment Strategy

A phased deployment strategy is proposed to ensure controlled scale, feedback incorporation, and measurable outcomes.

1) Phase 1 – Pilot Studies

Select state education boards, municipal health departments, and agricultural universities should lead pilots. Example applications include air quality microgrids, digital libraries, and mobile diagnostic centers.

2) Phase 2 – CSR and NGO Partnerships

Corporate Social Responsibility (CSR) arms of tech companies and NGOs can co-deploy and maintain repurposed device networks in smart city zones and tribal areas. Platforms like NITI Aayog’s Aspirational Districts Programme may provide ideal test beds.

3) Phase 3 – Institutional Scaling

Upon validation, national programs like Digital India, Ayushman Bharat, and NEP 2020 can integrate these models through public-private partnerships (PPPs). Central repositories for firmware, apps, and deployment best practices should be maintained by nodal agencies like MeitY.

C. Impact Measurement and Feedback Loops

Deployment success should be measured using:

- **Uptime Metrics**: Percentage of operational devices over time.
- **Service Impact**: Data collected (e.g., AQI reports, health visits logged, student engagement).
- **Community Feedback**: Participatory evaluations via surveys and digital forums.

Continuous monitoring will inform design iteration, app optimization, and policy fine-tuning.

VIII. FUTURE WORK

While this study presents a validated prototype and a conceptual model for reusing surplus Android smartphones in decentralized infrastructure, several avenues remain for deeper exploration, modeling, and cross-disciplinary research. This section outlines four key directions.

A. Formal Modeling and Simulation

To generalize deployment strategies and optimize network behavior, future research can employ:

- **Agent-Based Modeling (ABM)**: Simulate networks of reused smartphones acting as semi-autonomous agents performing sensing, computation, and coordination tasks under varying environmental and infrastructural constraints.
- **System Dynamics Modeling**: Understand trade-offs between reuse scale, device longevity, and power consumption in larger deployments.
- **Network Simulation**: Analyze latency, resilience, and throughput of hybrid communication layers (Wi-Fi, BLE, LoRa) in urban vs. rural environments.

Such modeling efforts can inform design parameters, hardware configurations, and policy guidelines for national-scale rollouts.

B. Economic and Environmental Analysis

While reuse intuitively reduces hardware cost and e-waste, quantifying this impact is essential.

- **Lifecycle Extension Savings**: Preliminary analysis shows that repurposing a smartphone costs **60–70% less** than purchasing a commercial IoT node with equivalent functionality.
- **Carbon Offset Estimation**: Avoiding new device production reduces emissions and electronic waste disposal burdens.
- **Cost-per-Node Benchmarking**: Future studies should develop standardized **cost vs. impact metrics** for public institutions and CSR sponsors.

This analysis would be instrumental for stakeholders including municipal authorities, policy makers, and funders evaluating scale-up viability.

C. Social and Ethical Research

Understanding the human and cultural dimensions of smartphone reuse is equally important:

- **Gendered Impacts**: Understand how device access and usage differ across gender, particularly in rural or marginalized settings.
- **Digital Literacy and Inclusion**: Explore usability improvements, especially for elderly users, children, or first-time technology adopters.
- **Linguistic and Cultural Design**: Create multi-lingual, culturally contextual interfaces for citizen-facing apps deployed on reused phones.

These studies will strengthen the techno-social innovation argument and ensure ethical, inclusive digital public goods.

D. AI Integration and Federated Learning

Advanced deployments can benefit from privacy-preserving, distributed machine learning:

- Enable collective intelligence across low-power devices.
- Improve model robustness in diverse, real-world settings.
- Support adaptive learning based on location-specific feedback.

Such integration enhances the resilience and scalability of AI at the edge.

IX. CONCLUSION

This paper presents a comprehensive theoretical and architectural framework for repurposing surplus Android smartphones as the foundation of a frugal, decentralized, and sustainable digital infrastructure in low-resource settings.

Motivated by India's high smartphone turnover, growing e-waste crisis, and digital infrastructure gaps, we argue that discarded smartphones, despite superficial hardware or software limitations, retain enough capability to serve as edge computing devices for public service applications.

We introduced three core constructs—techno-social innovation, frugal digital infrastructure, and decentralized edge ecology—to provide a conceptual vocabulary for this reuse paradigm. Across categorized use cases, we demonstrated that surplus devices can be deployed in fields such as healthcare, education, smart agriculture, air quality monitoring, and urban infrastructure, offering localized, low-cost alternatives to conventional digital systems.

A prototype deployment in Delhi validated the feasibility of this approach, showing that e-waste devices can be transformed into durable, solar-powered AQI sensing units. This deployment engaged the community, supported policy-relevant environmental data collection, and operated reliably for over three months with minimal intervention.

Our proposed four-layer system architecture—from the device to cloud—coupled with practical deployment strategies, standardization mechanisms, and privacy safeguards, lays the groundwork for scalable adoption. We also outlined policy pathways and suggested future research directions, including cost-benefit modeling, federated learning, and agent-based simulations.

This work bridges theoretical insight with on-ground validation, and contributes to the broader discourse on circular economy practices, digital inclusion, and sustainable ICT development. With the right ecosystem of policy support, community participation, and technical stewardship, India—and similar economies—can lead a new model of resilient digital public infrastructure built through reuse.

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