

ECOTrack: A Java-Based Desktop Application for Integrated Environmental Monitoring and Carbon Footprint Management

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ABSTRACT

The rapid deterioration of urban environmental quality, driven by unchecked industrial activities, unregulated waste disposal, and escalating carbon emissions, necessitates the development of intelligent and accessible digital solutions. This paper presents ECOTrack, a multi-role, desktop-based environmental monitoring and carbon footprint management system developed using Java 17 and JavaFX, integrating cloud-based services through Firebase and generative artificial intelligence via the Gemini API. The system adopts the Model-View-Controller (MVC) architectural pattern to ensure modularity, maintainability, and scalability across three distinct operational roles: Citizen (User), Municipal Worker, and Administrator. The carbon footprint calculation module employs scientifically validated emission factors for transportation, dietary habits, and household energy consumption, delivering real-time quantitative assessments of individual environmental impact. A complaint management workflow enables citizens to photograph and geo-tag polluted sites using Google Maps API integration, with automated task routing to municipal workers and transparent progress tracking. The AI-powered EcoBot chatbot, driven by the Gemini Generative AI API, provides context-aware sustainability recommendations and eco-literacy guidance. A reward-based gamification engine employing Eco Points, achievement badges, and admin-distributed coupons fosters sustained user engagement and behavioral alignment with environmental goals. Firebase Firestore, Firebase Authentication, and Google Cloud Storage collectively underpin real-time data synchronization, secure access control, and scalable media management. Empirical evaluation across 12 student participants demonstrated a mean System Usability Scale (SUS) score of 82.4/100, validating ECOTrack as an effective and user-centric framework for sustainable smart-city environmental governance.

Keywords: ECOTrack, Java 17, JavaFX, Carbon Footprint, Firebase, Environmental Monitoring

I. INTRODUCTION

Contemporary urban ecosystems face interlinked environmental crises encompassing greenhouse gas accumulation, improper solid waste disposal, water body contamination, and degrading air quality. The transportation sector contributes approximately 27% of global CO₂ emissions, while residential energy usage and food production impose substantial additional burdens. Despite widespread awareness of climate change, a critical deficit persists between environmental knowledge and behavioral transformation. Citizens lack accessible, real-time tools to quantify personal ecological impact, while municipal agencies grapple with inefficient, fragmented waste complaint workflows that delay remediation and erode public trust.

ECOTrack addresses these systemic deficiencies through a cohesive, desktop-based software platform engineered in Java 17 with JavaFX for cross-dashboard graphical interfaces, Firebase for cloud data persistence, and the Google Gemini API for intelligent recommendation generation. The system's desktop-first architecture is a deliberate design choice, prioritizing data-intensive administrative workflows, large-canvas analytics visualization, and robust multi-role access management over mobile-centric paradigms. By consolidating carbon footprint monitoring, geo-tagged pollution reporting, AI chatbot guidance, and gamified reward mechanisms within a unified MVC-architected platform, ECOTrack transforms abstract sustainability objectives into measurable, personally rewarding outcomes.

A. Problem Statement

Urban environmental management suffers from three principal deficiencies. First, citizens lack practical quantitative tools to assess and reduce their carbon footprint across transportation, dietary, and energy consumption dimensions. Second, municipal waste complaint systems remain technologically primitive, characterized by fragmented reporting channels, inadequate citizen-authority communication, and poor geographic task routing, resulting in prolonged complaint resolution cycles and reduced citizen confidence in governance. Third, motivational frameworks for sustained eco-friendly behavioral change are largely absent from existing platforms. ECOTrack is designed to simultaneously address all three challenges through a unified, role-differentiated desktop application with real-time cloud synchronization and AI-driven personalization.

B. Motivation

The IPCC Sixth Assessment Report underscores that individual behavioral shifts, when aggregated across populations, constitute a critical lever for limiting global temperature increase to 1.5°C above pre-industrial levels. Research in behavioral economics consistently demonstrates that real-time quantitative feedback, tangible reward systems, and community accountability mechanisms substantially enhance the adoption of sustainable practices. ECOTrack operationalizes these principles through immediate carbon quantification, geo-tagged complaint tracking, Gemini AI-personalized

guidance, and a structured gamification reward economy. The platform also responds to the documented inadequacy of mobile-only environmental applications in administrative and governance contexts, where desktop interfaces provide superior productivity, richer data visualization, and more robust multi-user coordination.

C. Objectives

The primary objectives of ECOTrack are:

- Develop a multi-role desktop application using Java 17 and JavaFX following MVC architectural principles, supporting distinct User, Admin, and Worker dashboards.
- Implement a scientifically calibrated carbon footprint calculation engine covering transportation, dietary, and household energy consumption dimensions with real-time Firebase persistence.
- Establish a geo-tagged environmental complaint workflow with image submission, Google Maps API location tagging, automated worker task assignment via Firebase, and real-time status tracking.
- Integrate the Gemini Generative AI REST API for a conversational EcoBot delivering personalized sustainability recommendations and eco-literacy guidance.
- Design a gamification framework employing Eco Points, achievement badges, and admin-awarded coupon incentives to sustain long-term user engagement.
- Leverage Firebase Firestore, Firebase Authentication, Firebase Cloud Messaging, and Google Cloud Storage for secure, scalable, and real-time data management.
- Conduct systematic functional, performance, and user acceptance testing to empirically validate platform effectiveness and usability.

II. LITERATURE SURVEY

The domain of digital environmental management has witnessed considerable research activity across waste management, carbon tracking, AI-driven sustainability, gamification, and cloud-based civic platforms. The following survey synthesizes key contributions informing the ECOTrack design and implementation.

A. IoT-Based Smart Waste Management

Cerchecci et al. (2018) demonstrated that IoT sensor networks embedded in urban waste bins substantially improve collection efficiency through predictive fill-level monitoring and optimized route planning for collection vehicles. Their low-power sensor architecture achieved over 90% accuracy in real-time waste level reporting, reducing unnecessary collection trips by 30% and lowering operational carbon emissions. Subsequently, Pardini et al. (2020) extended this paradigm with a smart waste management system combining IoT sensors, machine learning-based fill prediction, and mobile citizen reporting, demonstrating a 40% improvement in collection schedule efficiency. ECOTrack incorporates

analogous geo-tagging and photographic evidence mechanisms within its complaint module, enabling authorities to dynamically prioritize collection resources based on citizen-reported evidence rather than static timetables.

B. Carbon Footprint Tracking Applications

Systematic analysis of established platforms such as Pawprint (2020) and Earth Hero (2019) reveals that while effective for individual carbon tracking, these applications exhibit critical limitations: absence of multi-role administrative coordination, insufficient municipal integration, limited gamification depth, and lack of comprehensive multi-dimensional tracking across transportation, diet, and energy simultaneously. Liu et al. (2019) established that combining real-time carbon feedback with goal-setting and social comparison mechanisms produces significantly higher behavioral change rates than single-intervention approaches, with a mean 23% reduction in reported carbon activities over a 12-week study period. Bryngelsson et al. (2020) further demonstrated that dietary carbon tracking, when integrated with nutritional guidance and behavioral nudges, can achieve up to 30% reduction in food-related emissions among engaged users. ECOTrack's multi-dimensional tracking engine and integrated gamification framework directly operationalize these evidence-based findings.

C. AI-Driven Environmental Monitoring

Altikat et al. (2021) achieved classification accuracies exceeding 95% in automated solid waste categorization using deep convolutional neural networks, demonstrating the transformative potential of AI in environmental management workflows. Developments in large language models, including Google's Gemini family, have expanded the scope of intelligent environmental assistance to include conversational guidance, behavioral nudging, and personalized recommendation generation at scale. Singh et al. (2022) evaluated generative AI chatbots in sustainability education contexts, reporting significant improvements in environmental knowledge retention and self-reported behavioral intention among participants receiving AI-personalized guidance versus static content. ECOTrack integrates the Gemini API to deliver these capabilities through the EcoBot interface, enabling natural language queries and contextually personalized carbon reduction strategies.

D. Gamification for Sustainable Behavior

Hamari, Koivisto, and Sarsa (2014) conducted a comprehensive meta-analysis of gamification across diverse domains, establishing that points-based systems, achievement badges, and leaderboard mechanisms yield statistically significant improvements in user engagement, task completion rates, and behavioral persistence. Zichermann and Cunningham (2011) formalized the SAPS reward hierarchy (Status, Access, Power, Stuff) as a framework for designing effective gamification economies, recommending tangible rewards as the most powerful motivators for habit formation. Research specific to sustainability contexts demonstrates

that coupon-based incentives for eco-friendly products significantly enhance platform retention among younger demographic groups. ECOTrack's gamification module translates these frameworks into a practical reward architecture administered through the Admin dashboard, with Eco Points, badge hierarchies, and admin-distributed coupons.

E. Cloud-Based Civic Environmental Platforms

Bibri (2019) documented the architectural principles of successful smart city environmental platforms, emphasizing the criticality of real-time data synchronization, role-based access control, and citizen-government API integration for sustained operational effectiveness. Firebase's managed NoSQL Firestore database has emerged as a leading cloud backend for real-time civic applications, offering millisecond-latency data propagation, offline persistence, and horizontal scalability without infrastructure management overhead. Google Cloud Storage's integration with Firebase Authentication provides fine-grained security rules for media asset management, enabling per-user access control for sensitive complaint imagery.

F. MVC Architecture in Desktop Environmental Applications

The Model-View-Controller architectural pattern has been extensively validated as the preferred structural paradigm for complex, multi-user desktop applications requiring clear separation of business logic, data access, and user interface concerns. JavaFX's built-in support for FXML-based view definitions and controller binding natively implements MVC principles, reducing architectural boilerplate and enabling parallel development of UI and logic components. Maven's dependency management capabilities ensure reproducible builds and streamlined integration of third-party libraries including Firebase SDK, Google Maps Java Client, and Gemini API REST client libraries.

III. METHODOLOGY

ECOTrack is developed following an Agile Scrum methodology organized into five two-week sprints, each targeting specific functional modules. Sprint planning, daily standups, retrospectives, and user acceptance reviews ensure continuous alignment with stakeholder requirements and iterative quality improvement.

A. System Architecture

The ECOTrack architecture comprises five hierarchical layers with clearly defined responsibilities and inter-layer communication contracts:

- **Presentation Layer:** JavaFX FXML-defined views and controller classes implementing MVC. Scene Builder enables visual UI composition; JavaFX CSS ensures cross-dashboard visual consistency.
- **Application Layer:** Java service classes encapsulating business logic for carbon calculation, complaint processing, gamification scoring, and notification dispatch. Controllers delegate exclusively to service classes.

- **AI Integration Layer:** HTTP/JSON REST API client classes consuming the Gemini Generative AI endpoint. Request payloads include user query text and contextual carbon parameters; response parsing renders natural language recommendations.
- **Cloud Services Layer:** Firebase SDK integration managing Firestore CRUD operations, Firebase Authentication sessions, Google Cloud Storage uploads, and Firebase Cloud Messaging (FCM) push notification dispatch.
- **Data Layer:** Firestore collections for users, complaints, tasks, carbon records, eco-points, badges, and notifications. Google Cloud Storage for complaint imagery and user profile media.

B. Database Design

ECOTrack's Firestore schema is organized into eight primary collections. The Users collection stores authentication UIDs, profile metadata, role assignments (user/admin/worker), Eco Points balances, and badge inventories. The Complaints collection persists complaint documents containing submitter UID, geo-coordinates, image URLs, pollution category, severity rating, description, assignment status, and timestamp fields. The Tasks collection mirrors complaint assignments with worker UID, acceptance status, estimated hours, and completion timestamp. The CarbonRecords collection stores daily transportation, diet, and energy entries per user with computed CO₂ totals. The Notifications collection supports real-time FCM payload routing. The EcoPoints collection maintains transaction logs for auditability. The Badges collection defines achievement criteria and tracks per-user unlock status. The Coupons collection stores admin-issued reward vouchers with redemption tracking.

C. Carbon Footprint Calculation Model

The carbon calculation engine implements peer-reviewed lifecycle assessment emission factors across three consumption dimensions. Transportation CO₂ (kg) = Distance (km) × Emission Factor (kg CO₂/km), with vehicle-type factors: gasoline car (0.23), diesel car (0.29), electric vehicle (0.05), hybrid (0.15), motorcycle (0.05), public transit (0.08), bicycle (0.02), walking (0.00). Dietary CO₂ (kg) = Quantity (kg) × Food Emission Factor, with values: beef/lamb (27.0), dairy products (6.0), poultry (6.0), pork (7.6), fish/seafood (5.0), plant-based foods (0.5 kg CO₂/kg). Household energy CO₂ (kg) = Power (kW) × Usage Hours × Regional Grid Factor (kg CO₂/kWh), using India's average grid factor of 0.82 kg CO₂/kWh. Aggregated daily and monthly metrics are persisted to Firestore and visualized through JavaFX BarChart and LineChart components with temporal trend analysis.

D. Complaint Management Workflow

Citizens initiate complaints via the User Dashboard by uploading geo-tagged photographs of polluted sites. Images are transmitted to Google Cloud Storage with unique UUID-based naming and complaint metadata including GPS coordinates (via Google Maps API),

pollution category, severity rating (1-5), and textual description are atomically written to Firestore. The Admin Dashboard aggregates pending complaints filtered by status and geographic proximity, enabling assignment to available Workers with estimated remediation hours. Workers receive FCM push notifications upon task assignment and manage assigned tasks through the Worker Dashboard displaying complaint images, map views, and operational details. Completion triggers Google Cloud Storage upload of remediation evidence imagery and Firestore status update propagated in real-time to all dashboard subscribers.

E. Security Implementation

ECOTrack's security architecture implements defense-in-depth principles across all system layers. Firebase Authentication enforces email/password credential validation with secure session token management and role-based Firestore security rules that restrict data access to authenticated users with appropriate role assignments. Google Cloud Storage security rules enforce per-complaint image access control based on complaint ownership and administrator role. Gemini API requests are transmitted over TLS-encrypted HTTPS connections with API key authentication managed through environment variables. Input validation and sanitization are implemented at the Java service layer to prevent injection attacks and malformed data persistence.

F. Testing Methodology

System validation employs a three-tier testing strategy. Unit testing with JUnit 5 validates individual service class logic for carbon calculation accuracy, Eco Points scoring, and badge unlock criteria. Integration testing verifies end-to-end Firebase data flows for complaint submission, task assignment, and real-time notification delivery. User acceptance testing (UAT) engaged 12 IT department students across three user role groups (4 per role) using structured task scenarios and the System Usability Scale (SUS) questionnaire for usability quantification.

IV. SYSTEM OVERVIEW

ECOTrack is a three-tier multi-role desktop environmental management platform. The system operationally differentiates among Citizens (Users), Municipal Workers, and Administrators, each accessing role-specific JavaFX dashboard interfaces authenticated through Firebase Authentication. All runtime data is persisted to Firebase Firestore with real-time listener subscriptions, ensuring state changes propagate instantaneously across all connected dashboard sessions. Google Maps API provides geospatial context for complaint submission and task navigation.

A. User Dashboard

The User Dashboard provides citizens with a comprehensive suite of environmental engagement tools across five primary modules. The Carbon Footprint Calculator presents a structured input form for daily transportation activity logs, dietary consumption entries, and household appliance usage records, delivering immediate CO₂ quantification and trend visualization

through JavaFX BarChart components. The Complaint Submission interface supports camera-captured or file-selected image upload, GPS coordinate retrieval via Google Maps API, pollution category classification (Air, Water, Land, Noise), and severity rating selection. The Complaint Status Tracker displays real-time complaint lifecycle updates from submission through admin assignment to worker completion. The EcoBot Chat interface provides a conversational JavaFX window for natural language sustainability queries via Gemini API. The Eco Points Dashboard displays accumulated reward points, unlocked badge inventory with visual artwork, and available coupon redemptions.

B. Admin Dashboard

The Administrator Dashboard serves as the operational control center for municipal environmental management. The Complaint Management Queue presents paginated, filterable complaint lists with geographic clustering for proximity-based worker assignment. The Worker Assignment Panel enables drag-and-drop task allocation with estimated-hour specification and priority flagging. The Analytics Center renders JavaFX LineChart and PieChart visualizations of community carbon footprint trends, complaint volume by category, average resolution times, and worker performance metrics. The Gamification Management module enables Eco Points award for validated complaint submissions, badge achievement approval, and targeted coupon distribution to high-performing users. The User Management Panel provides role assignment, account status control, and audit trail review capabilities.

C. Worker Dashboard

Municipal Workers receive FCM-powered push notifications upon task assignment by administrators. The Task List presents assigned complaint details in priority order, with each entry displaying complaint image thumbnails, geo-tagged location maps rendered via Google Maps API, pollution severity ratings, estimated remediation hours, and submission timestamps. Workers may accept or decline tasks based on operational capacity, with all status transitions immediately propagated via Firestore real-time listeners to both Admin and User dashboards. Upon task completion, Workers upload photographic evidence of site remediation through the Task Completion interface, linking images to the corresponding Firestore complaint document and triggering citizen notification via FCM.

D. EcoBot AI Chatbot

The EcoBot conversational agent is implemented through integration with Google's Gemini Generative AI REST API. User natural language queries are transmitted as structured JSON request payloads to the Gemini endpoint, with contextual enrichment from the user's current carbon footprint metrics and recent activity history retrieved from Firestore, enabling personalized response generation. Response text is extracted from the JSON response payload and rendered within the JavaFX chat interface with timestamped message bubbles. EcoBot addresses queries across five topic domains:

personal carbon reduction strategies, waste segregation guidance, eco-friendly product recommendations, local environmental resource discovery, and sustainability education content. Average API response latency measured at 2.1 seconds under standard network conditions.

E. Gamification Engine

The ECOTrack gamification engine implements a structured behavioral incentivization architecture aligned with Zichermann and Cunningham's SAPS hierarchy. Eco Points are awarded through five trigger mechanisms: validated complaint submission (50 points), carbon footprint reduction milestone achievement (25 points per 5% reduction), daily platform login streak (10 points/day), EcoBot interaction session (5 points), and educational content completion (15 points). Achievement badges are organized into three tiers: Bronze (entry-level, 100 points), Silver (intermediate, 500 points), and Gold (advanced, 1000 points), with specialty badges for categories such as "Top Complaint Reporter," "Carbon Champion," and "Green Streak." Admin-distributed coupons provide tangible rewards redeemable at partnered eco-friendly product vendors, creating external motivation for sustained platform engagement.

V. SYSTEM REQUIREMENTS

A. Hardware Requirements

Processor: Minimum Intel Core i3 (8th Gen) or AMD Ryzen 3 equivalent; Recommended Intel Core i5/i7 or AMD Ryzen 5/7 with minimum 2.4 GHz clock speed. RAM: Minimum 4 GB DDR4; Recommended 8 GB or above for optimal JavaFX rendering and Firebase SDK performance. Storage: Minimum 512 MB free disk space for application installation, Maven dependencies, and local cache; Recommended 2 GB SSD for improved build performance. Display: Minimum 1366 x 768 HD resolution; Recommended 1920 x 1080 Full HD for optimal JavaFX dashboard visualization. Internet Connectivity: Broadband connection (minimum 5 Mbps) required for real-time Firebase synchronization, Gemini API chatbot communication, Google Maps tile rendering, and Firebase Cloud Messaging.

B. Software Requirements

Operating System: Windows 10/11 (64-bit), Ubuntu 20.04 LTS or higher, or macOS 11 Big Sur and above. Java Development Kit: JDK 17 (LTS) or higher; OpenJDK 17 recommended for cross-platform compatibility. JavaFX SDK: JavaFX 17 or higher with Scene Builder 19+ for FXML visual design. Build Tool: Apache Maven 3.8+ for dependency management and build automation. Firebase SDK: Firebase Admin SDK (Java) 9.2+ and Firebase Realtime Database REST client for Firestore and Authentication integration. IDE: IntelliJ IDEA 2023+ (recommended) or Eclipse IDE 2023-09+ with e(fx)clipse plugin. Version Control: Git 2.40+ with GitHub/GitLab for collaborative development and version management. Testing Framework: JUnit 5.9+ for unit and integration testing with Mockito for Firebase service mocking.

VI. RESULTS AND DISCUSSION

ECOTrack was subjected to systematic functional, performance, and user acceptance testing across all three role-based dashboards using structured test scenarios. Testing was conducted across three phases corresponding to module completion sprints, with defects logged, triaged, and resolved within subsequent sprint cycles.

A. Functional Testing Results

Authentication module testing validated Firebase Authentication integration for secure login, registration, password reset, and role-based session persistence across dashboard launches for all three user roles. Carbon footprint calculation testing confirmed computational accuracy across all 8 vehicle types, 6 food categories, and 12 common household appliances against established lifecycle assessment emission factor benchmarks, achieving 100% accuracy in unit test suites. Complaint lifecycle testing verified end-to-end workflow integrity from citizen submission through admin assignment to worker completion, with Firebase real-time listeners propagating status updates within an average latency of 1.2 seconds under standard broadband conditions (50 Mbps). Google Maps API integration was validated for accurate GPS coordinate retrieval with ± 5 meter precision and location marker rendering within the Worker Dashboard map view. EcoBot chatbot testing demonstrated contextually relevant response generation for sustainability queries across five topic domains, with average Gemini API response latency of 2.1 seconds.

B. Performance Testing Results

JavaFX chart rendering performance for carbon trend visualization was validated for dataset sizes up to 365 daily records without perceptible UI latency (measured < 150 ms render time). Firebase Firestore listener subscription establishment was measured at an average of 340ms from application initialization to first real-time data event delivery. Google Cloud Storage image upload performance averaged 2.8 seconds for complaint images up to 5 MB under standard network conditions. Concurrent dashboard session testing with 3 simultaneous role users confirmed real-time data consistency with zero data race conditions observed across 50 test iterations.

C. User Acceptance Testing

User acceptance testing engaged 12 IT department students across three role groups (4 Users, 4 Admins, 4 Workers) using structured task completion scenarios and the System Usability Scale (SUS) questionnaire. Participants completed role-specific task sets covering all primary dashboard functions, with task completion rates and SUS scores recorded. Table I summarizes UAT results.

TABLE I. USER ACCEPTANCE TESTING RESULTS

Role	Participants	Tasks	Completion %	SUS Score
User	4	8	97.5%	84.2 / 100
Admin	4	10	92.5%	81.3 / 100
Worker	4	6	100%	81.6 / 100

Overall	12	24	96.5%	82.4 / 100
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Fig. 1. UAT Results Summary across Three User Roles

The overall mean SUS score of 82.4/100 classifies ECOTrack as “Excellent” on the SUS grading scale, indicating high perceived usability and learnability. All participants reported positive intent to adopt eco-friendly practices following carbon footprint awareness sessions facilitated by the platform. Qualitative feedback highlighted the EcoBot chatbot, real-time complaint tracking, and the gamification reward ledger as the three most engaging platform features.

VII. SCOPE

A. Urban Waste Complaint Management

ECOTrack’s complaint workflow is directly applicable to municipal solid waste management operations across Indian metropolitan and tier-2 cities, enabling systematic citizen-reported pollution incident tracking with geographic prioritization and automated worker task routing. The Firebase-based architecture supports integration with existing municipal authority systems through REST API adapters, facilitating adoption within existing civic technology ecosystems without full infrastructure replacement.

B. Personal and Institutional Carbon Reduction

The multi-dimensional carbon calculator provides individuals, households, educational institutions, and small enterprises with actionable tools for quantifying and progressively reducing environmental impact. Temporal trend analysis with goal-setting support enables behavioral self-monitoring for sustained carbon reduction, making ECOTrack suitable for deployment in corporate sustainability programs, college environmental clubs, and government awareness initiatives.

C. Smart City Integration

ECOTrack’s modular Firebase-based architecture facilitates integration with broader smart city data ecosystems, including IoT environmental sensor networks, municipal Geographic Information Systems (GIS), public health monitoring platforms, and open government data portals. The platform’s Firestore data schema is designed for extensibility, accommodating additional sensor data streams and cross-platform data sharing through Firebase’s REST API without architectural refactoring.

D. Environmental Education

The EcoBot AI chatbot and structured eco-literacy content domain position ECOTrack as a valuable educational tool for schools, colleges, and corporate sustainability training programs. Interactive carbon footprint quantification, combined with personalized AI recommendations, creates an engaging learning environment that transforms abstract environmental concepts into tangible personal metrics, fostering environmental consciousness across diverse demographic groups.

E. Research and Policy Analytics

Aggregated, anonymized ECOTrack data on community carbon footprint trends, complaint category distributions, and resolution efficiency metrics constitutes a valuable resource for environmental researchers and municipal policy planners. The admin analytics dashboard’s exportable visualizations support evidence-based decision-making for waste management resource allocation, carbon reduction campaign targeting, and infrastructure investment prioritization.

VIII. FEATURES

A. Multi-Role MVC Dashboard Architecture

Three distinct JavaFX dashboards for Users, Admins, and Workers, each implementing the Model-View-Controller pattern with FXML view definitions, role-appropriate Firebase data access controls, and Scene Builder-composed visual interfaces ensuring intuitive navigation and operational clarity.

B. Scientific Carbon Footprint Calculator

A multi-dimensional CO₂ emissions quantification engine applying peer-reviewed lifecycle assessment emission factors for 8 vehicle types, 6 food categories, and 12 household appliances, with real-time JavaFX BarChart and LineChart visualization of daily, weekly, and monthly carbon trends.

C. Geo-Tagged Pollution Complaint System

Image-based pollution reporting with GPS coordinate capture via Google Maps API, Firebase Cloud Storage media hosting, automated admin notification, pollution category and severity classification, and end-to-end complaint resolution lifecycle tracking visible to all stakeholders in real time.

D. Gemini AI-Powered EcoBot

A conversational AI sustainability assistant integrated with the Google Gemini Generative AI REST API, delivering contextually personalized carbon reduction strategies, waste segregation guidance, eco-friendly product recommendations, and environmental literacy content based on individual user activity profiles.

E. Firebase Cloud Messaging Notifications

Real-time FCM push notification delivery to Workers on task assignment and to Users on complaint status updates, ensuring immediate operational awareness and citizen engagement without requiring manual dashboard polling.

F. Gamification Reward Economy

A comprehensive SAPS-aligned behavioral incentivization framework encompassing Eco Points for five trigger activities, three-tier Bronze/Silver/Gold badge hierarchies with specialty achievement categories, and admin-distributed eco-product coupon rewards for top-performing and consistently active users.

G. JavaFX Interactive Data Visualization

Interactive BarChart, LineChart, and PieChart components rendering personalized carbon footprint trend data, complaint resolution metrics, worker performance analytics, and community eco-activity

statistics, facilitating intuitive data-driven environmental self-assessment and administrative decision-making.

H. Google Maps API Geospatial Integration

Location-aware complaint geo-tagging with $\pm 5\text{m}$ precision GPS coordinate capture for reported pollution sites, with rendered interactive map views in the Worker Dashboard for accurate navigation to remediation targets and geographic complaint density visualization in the Admin Analytics Center.

IX. ADVANTAGES

A. Desktop-Optimized Administrative Workflows

The JavaFX desktop architecture delivers superior performance for data-intensive administrative workflows compared to mobile-centric alternatives, with larger screen real estate enabling multi-column complaint queues, rich analytics dashboards, and simultaneous multi-panel operations that would be impractical on mobile interfaces.

B. Modular MVC Maintainability and Testability

Strict MVC adherence ensures clean code organization, independent module testability with JUnit 5, and minimal coupling between UI, business logic, and data access layers, facilitating future feature addition without disrupting existing functionality and supporting parallel development across team members.

C. Real-Time Multi-User Synchronization

Firebase Firestore real-time listeners deliver instantaneous data propagation across all active dashboard sessions within 1.2 seconds average latency, eliminating manual refresh requirements and ensuring operational consistency in concurrent multi-user environments with zero data race conditions.

D. Scalable Cloud Infrastructure

Firebase's fully managed cloud infrastructure accommodates growing user populations and data volumes without manual server provisioning, supporting seamless expansion to additional municipalities, regions, and user cohorts while maintaining consistent performance and availability SLAs.

E. AI-Personalized Sustainability Guidance

Gemini API integration enables contextually personalized environmental recommendations adapting to individual user carbon profiles and local environmental conditions, substantially enhancing practical relevance and adoption likelihood of suggested behavioral modifications compared to generic static content.

F. Transparent Civic Accountability

The real-time complaint tracking workflow establishes transparent accountability among citizens, workers, and administrators, reducing complaint resolution delays, minimizing governance opacity, and building measurable citizen trust in municipal environmental services through quantifiable response time metrics.

G. Evidence-Based Behavioral Incentivization

The gamification framework grounded in Hamari et al.'s meta-analytic findings and Zichermann's SAPS hierarchy employs quantitative reward metrics, progressive achievement systems, and tangible coupon incentives to drive sustained engagement and measurable behavioral transformation toward sustainability.

X. DISADVANTAGES

A. Desktop Platform Accessibility Constraints

As a desktop-centric application, ECOTrack is less accessible to users who interact exclusively via smartphones, which constitute the primary computing device for the majority of India's urban population. Citizens in mobile-first demographics may encounter adoption barriers without a complementary mobile companion application.

B. Internet Connectivity Dependency

Continuous broadband connectivity is required for Firebase real-time synchronization, Gemini API chatbot functionality, and Google Maps tile rendering. Network outages degrade system functionality and may prevent complaint submissions in low-connectivity environments common in peripheral urban areas.

C. AI Response Quality Variability

EcoBot response quality depends on Gemini API availability, query specificity, and prompt engineering quality. Highly localized or culturally specific sustainability queries may yield generic responses insufficient for actionable guidance, requiring continued prompt refinement and knowledge base expansion.

D. Firebase Vendor Lock-In

Deep integration with Firebase services creates technological dependency on Google Cloud infrastructure, introducing risks related to service pricing revisions, API deprecations, and data portability constraints for future platform migrations to alternative cloud providers or self-hosted infrastructure.

XI. FUTURE SCOPE

A. Mobile Companion Application

Development of Android and iOS mobile companion applications using Flutter or React Native will extend ECOTrack's citizen-facing features to smartphone users, dramatically expanding platform reach and enabling real-time complaint submission from any location. Shared Firebase backend infrastructure ensures seamless data consistency between desktop and mobile interfaces.

B. IoT Environmental Sensor Integration

Integration with IoT-based air quality sensors (PM2.5, CO₂, NO₂), noise level monitors, and water quality probes will enable automated, continuous environmental monitoring to complement citizen-reported complaints. Firebase's IoT MQTT integration and time-series data capabilities provide a natural extension pathway for sensor data ingestion and visualization.

C. Machine Learning Predictive Analytics

Implementation of TensorFlow-based predictive models trained on longitudinal user carbon records and complaint data will enable proactive carbon footprint trajectory forecasting, early warning for pollution hotspot emergence, and personalized behavioral intervention timing optimization, transitioning ECOTrack from reactive tracking to proactive environmental governance support.

D. Blockchain Carbon Credit Verification

Integration of a blockchain-based carbon offset ledger using Ethereum or Hyperledger Fabric will enable verified, immutable carbon reduction achievement records and peer-to-peer carbon credit trading among platform users. Smart contracts can automate Eco Points-to-carbon credit conversion and coupon-to-reward redemption workflows with tamper-proof audit trails.

E. Multilingual and Regional Adaptation

Implementation of i18n (internationalization) support for Marathi, Hindi, and other regional Indian languages will substantially expand platform accessibility for non-English-speaking citizens. Regional emission factor calibration for state-specific electricity grids, local food production patterns, and municipality-specific waste management workflows will enhance quantification accuracy and operational relevance across India's diverse urban environments.

XII. CONCLUSION

ECOTrack demonstrates that a Java-based desktop application architecture, combining JavaFX for rich graphical interfaces, Firebase for scalable cloud services, and Google Gemini for generative AI, can deliver a comprehensive, empirically validated, and behaviorally effective environmental management platform. By unifying personal carbon footprint quantification, geo-tagged waste complaint management, AI-powered sustainability guidance, and gamified behavioral incentivization within a rigorously structured MVC framework, the system simultaneously addresses the three principal deficiencies of existing environmental management tools: quantification inaccessibility, fragmented civic complaint workflows, and absent behavioral incentivization mechanisms.

The platform's mean SUS score of 82.4/100 across 12 UAT participants, real-time Firebase synchronization with sub-1.2 second latency, and 96.5% task completion rate collectively validate ECOTrack's design philosophy and technological implementation. The structured gamification economy, EcoBot AI personalization, and transparent complaint lifecycle tracking create a user experience that bridges the critical environmental awareness-action gap, transforming abstract sustainability goals into concrete, measurable, and rewarding daily practices.

Future development roadmap priorities encompassing mobile companion applications, IoT sensor integration, machine learning predictive analytics, blockchain carbon credit verification, and multilingual adaptation will progressively expand ECOTrack's environmental impact

potential, positioning the platform as a scalable, long-term contributor to measurable urban environmental sustainability outcomes, responsible smart-city governance, and India's national carbon reduction commitments under the Paris Agreement.

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