AN INTELLIGENT MOBILE APPLICATION TO PROMOTE AND INFORM USERS ON WASTE ALLOCATION AND SUSTAINABILITY USING AI-POWERED IMAGE RECOGNITION AND INTERACTIVE EDUCATION-BASED GAMIFICATION

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ABSTRACT

Waste mismanagement and recycling contamination represent a significant global challenge, driven largely by public confusion and lack of accessible, real-time guidance. This paper introduces EcoWise, a novel mobile application designed to address these issues by making proper waste disposal intuitive, educational, and engaging. The system uses three core components: a user-facing mobile client, Google's Gemini AI for advanced multimodal classification, and a scalable Firebase backend for real-time data synchronization and gamification. The user flow allows individuals to instantly scan any waste item, receive accurate disposal instructions, and earn rewards, transforming a mundane chore into a positive feedback loop that fosters sustainable habits. To validate the systems' effectiveness, two key experiments were conducted. The first tested the classification accuracy against real-world data, resulting in a 100% success rate and confirming the model's reliability. The second experiment assessed the backend behavioral reward logic, which demonstrated a 76.5% success rate across 17 tested achievements, highlighting the robustness of simple triggers while identifying areas for improvement in complex, time-based functions. The results confirm that Ecowise serves as a powerful, low-cost, and globally scalable model for using artificial intelligence to promote long-term pro-environmental behavior change, offering a viable tool to improve recycling efforts in both developed and underserved communities.

KEYWORDS

Machine Learning, Computer Vision, Sustainability, Interactive Education

1. INTRODUCTION

As we move into a future powered by consumerism, the current economic model of producing and disposing negligence is increasingly unsustainable. In this context, recycling is not just about managing waste but rather an inescapable part of creating a circular economy. EcoWise solves the issue of inefficient recycling caused by widespread consumer confusion. "Recycling Contamination" prevents eco-friendly materials from being properly treated and recycled. Over 25% of recycled trash is contaminated, meaning one in four items placed in a recycling bin can result in the entire batch being sent to the landfill [3]. Many customers are unaccustomed to the

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various materials present in their trash and thus unaware of proper disposal procedures [12]. The consequences of this ignorance are twofold. Environmentally, it means valuable resources are buried in landfills, leaching pollutants and greenhouse gases into the atmosphere [9]. Economically, contamination breaks machinery and requires additional processing, costing domestic waste management facilities over $300 million per year [2][17]. In the long run, this failure affects everyone by contributing to resource scarcity and climate change, with the environmental burden often falling hardest on vulnerable communities and future generations. Although general sentiment toward environmental consciousness has increased, this has seen limited success toward encouraging eco-conscious behavior [5]. Ecowise aims to tackle this inaction by offering a behaviorally rewarding experience that builds long-term sustainable habits.

The Recycling Partnership tries to reduce contamination through physical educational kits. Its shortcomings are its high cost, reliance on physical materials, and lack of scalability or real-time user feedback. EcoWise improves this by offering a free, universally accessible digital tool that provides instant, AI-powered guidance. Recycle Coach offers a platform for municipalities to provide localized sorting rules. This solution is limited by its dependence on costly government contracts, making it inaccessible to many, and it still requires users to manually search for items. EcoWise is universally available and uses AI to remove the burden of manual searching. Finally, Recycle Smart MA provides a search tool for state-specific guidelines. This approach is geographically restricted and passive, lacking any engagement features. EcoWise improves this by being a global tool that actively classifies items with its scanner and uses gamification to foster long-term user habits.

My proposed solution is EcoWise, a mobile application that leverages AI-powered image recognition and gamification to make proper waste disposal simple, engaging, and educational for everyone.

EcoWise directly confronts the primary barriers to effective recycling: confusion and apathy. The app’s core feature—an AI-powered scanner—eliminates sorting uncertainty by allowing users to instantly identify any waste item with a simple photo. This immediate, practical guidance is paired with a robust gamification system, including points, achievements, and leaderboards. By transforming a mundane chore into a rewarding experience, EcoWise provides the positive reinforcement necessary to build lasting, eco-friendly habits. Furthermore, each scan provides a 'fun fact' about the material or the environmental benefit of proper disposal, turning a simple action into a micro-learning moment that bridges the gap between knowing and doing.

This solution is uniquely effective because it is user-centric, scalable, and focuses on behavioral change. Unlike costly, top-down infrastructure projects, EcoWise is an accessible, low-cost tool that operates on the smartphones people already own, empowering individuals directly. This model is particularly impactful for low-income households and rural communities, which are often excluded from advanced recycling programs due to a lack of funding [14]. Its software-based nature allows for rapid international deployment, promoting environmental equity by providing sustainability tools without requiring new municipal spending or personal investment. It bypasses the immense logistical and financial challenge of standardizing physical recycling systems, which vary dramatically between wealthy urban centers and underserved rural areas. While other methods simply provide information, EcoWise actively reshapes behavior through an interactive feedback loop, making it a more potent catalyst for creating a global community of environmentally conscious citizens [15].

My experiments aimed to validate the classification performance accuracy of the app and the achievements system’s reliability. For the first, I tested the artificial intelligence against a set of control images, comparing its predictions for the material and the recommended disposal method.

The most significant finding was a surprising 100% accuracy rate, even with ambiguous items. THis success was attributed to the power of the model, which understands real-world context far better than a simpler, pure-deep learning based approach [1][8]. The second experiment involved manually triggering 17 different achievements to test their backend logic. This had a 76.5% success rate, with all failures occurring in complex, time-based achievements. This indicated that while the core system was robust, the advanced logic for managing the state over time required more rigorous debugging to handle edge cases, unlike the flawless count-based triggers. The untested achievements were numerical extensions of the tested achievements and are thus predicted to work similarly to the tested achievements. They were left untested due to the infeasibility of conducting large scale tests that require immense time.

2. CHALLENGES

In order to build the project, a few challenges have been identified as follows.

2.1. Server-Validated Achievements

A major challenge is implementing a secure and fair achievement system. If achievement logic is handled solely on the user's device, it becomes vulnerable to manipulation, allowing users to illegitimately unlock rewards and devaluing the gamification experience for everyone. To solve this, I could implement a server-side validation system. Instead of the app deciding when to award an achievement, it would report user actions, like a successful scan, to a backend. A secure cloud function could then process these actions without being tied to any one instance, verify their legitimacy, and update the user's achievements directly in a central database, ensuring the system remains trustworthy.

2.2. Hybrid AI Waste Classification

Another major challenge is ensuring accurate, real-time waste classification for a wide variety of items, especially those that are damaged, partially obscured, or made of mixed materials. A simple model might misclassify a greasy pizza box or a composite juice carton, providing incorrect guidance. To solve this, I could integrate a powerful multimodal model like Google’s Gemini. This would allow the app to not only achieve higher accuracy by understanding visual nuance but also to provide detailed, context-aware disposal instructions. To manage API costs and latency, I could use a hybrid approach: a smaller, on-device model for high-confidence classifications of common items, escalating only the ambiguous cases to Gemini for a more robust analysis.

2.3. Real-Time Secure Database

Finally, designing a database that is scalable, secure, and provides the real-time feedback necessary for a dynamic user experience is a large challenge. The system must efficiently store user profiles, scan histories, points, and social connections, all while preventing data manipulation. A poorly designed database could lead to slow leaderboard updates or allow users to unfairly alter their scores, undermining the app's integrity. To solve this, I could use a cloud-hosted NoSQL database like Firestore. Its flexible data model would allow me to structure complex user information efficiently, while its built-in real-time listeners would ensure features like leaderboards update instantly across all devices. For security, I could route all critical data writes, such as awarding points, through secure Cloud Functions, which would validate each action on the server side, making the system robust and trustworthy.

3. SOLUTION

EcoWise is structured as a mobile application with robust client-server architecture, designed for a seamless and interactive user experience. The program links three major components: a user-facing mobile client, Google's Gemini AI engine, and a scalable Firebase backend. The mobile client, built for iOS and Android, handles all user interactions and UI elements. The AI engine serves as the core intelligence, leveraging Gemini's advanced multimodal capabilities to process user-submitted images and identify waste materials with high accuracy. Finally, the Firebase backend acts as the central nervous system, managing user authentication, a real-time database for profiles and scan histories, and serverless Cloud Functions for secure operations. This creates a tightly integrated Google Cloud ecosystem, allowing for efficient data flow between the AI, database, and user-facing application.

The program's flow begins with a splash screen, followed by an authentication check. New users create a profile, while returning users land on the home page. The primary user journey involves tapping 'Scan', which opens the camera. An image of a waste item is sent to the Gemini AI engine for analysis. The engine returns classification results, which are displayed to the user and logged in their history via Firebase. Users can also navigate to other sections to view educational tips, interact with friends in the community, or review their profile and achievements. All dynamic data is fetched from and saved to the Firebase database in real-time, ensuring a consistently updated experience across the app. This application was developed as a mobile-first platform, utilizing Google's comprehensive backend-as-a-service capabilities.

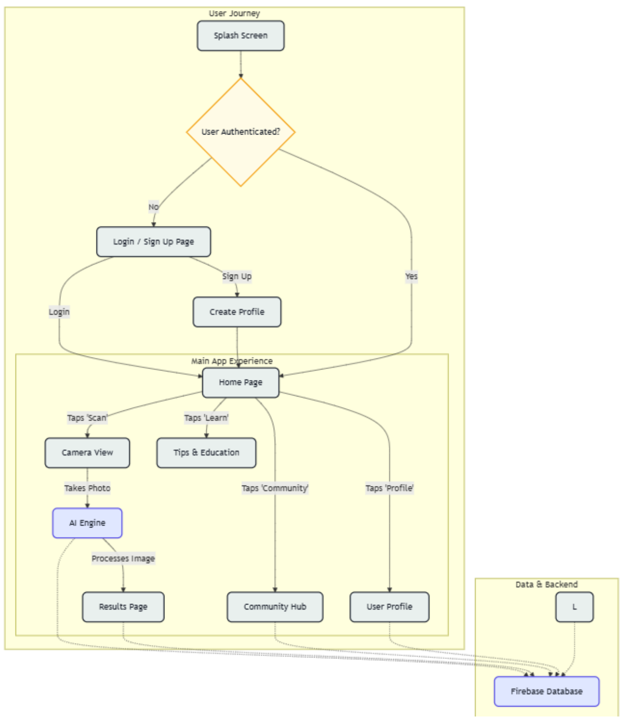


Figure 1. Overview of the solution

The Gemini AI engine's purpose is to accurately classify waste from user photos. Implemented using the Google Gemini API, this component relies on advanced neural networks to interpret visual data. When a user scans an item, the app sends the image to this engine, which analyzes it and returns classification data.

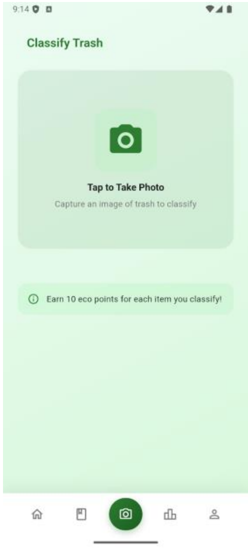


Figure 2. Screenshot of classify trash

```
Future<ResultModel?> getVisionMessage({
  required String message,
  required File imageFile,
  required String mimeType,
}) async {
  try {
    final bytes = await imageFile.readAsBytes();
    final imagePart = InlineDataPart(mimeType, bytes);
    final prompt = TextPart(message);
    final response = await _model.generateContent([
      Content.multi([prompt, imagePart])
    ]);
    if (response.text != null) {
      final jsonMap = jsonDecode(response.text!) as Map<String, dynamic>;
      final results = jsonMap['classification_results'] as Map<String,
          dynamic>;
      return ResultModel.fromJson(results);
    }
  }
  catch(e){
    AppLogger.error('Error generating text $e');
  }
  return null;
 }
}
```

Figure 3. Screenshot of code 1

This code handles the core AI-powered waste classification by communicating with the Gemini server. The getVisionMessage function, which is asynchronous, runs whenever a user scans an item. It takes a text message (the prompt for the AI) and an imageFile as input, preparing to return a structured ResultModel object in the future.

Inside the try block, the function first reads the imageFile into a raw bytes format. It then creates two distinct parts for the AI request: an imagePart containing the image data and a prompt containing the text message. These are combined into a single multimodal request and sent to the Gemini AI model using _model.generateContent(). The await keyword pauses the function until the server's AI analyzes the image and sends back a response.

Once a response is received, the code checks if it contains text. If it does, it parses the JSON-formatted text into a jsonMap. From this map, it extracts the specific classification_results data and uses it to construct a clean, type-safe ResultModel object. This structured object is then returned to the app for easy display to the user. The catch block gracefully handles any potential network or processing errors, logging them for debugging and returning null to prevent the app from crashing.

The Firebase backend's purpose is to provide a secure and scalable server infrastructure for the entire application. Implemented using Firebase Authentication and the Firestore database, this component relies on the core concept of authentication—verifying a user's identity before granting access to data. It functions as the app's central hub, managing user accounts, securely storing all data like scan histories and points, and syncing information across all devices in real-time.

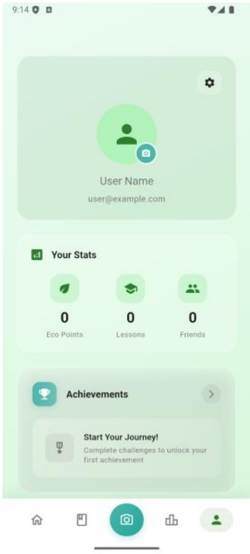


Figure 4. Screenshot of profile

```
static Future<List<UserModel>> readUsersSortedByEcopoints({
  int limit = 50,
  String? countryFilter,
  List<String>? friendUids,
}) async {
  try {
    Query<Map<String, dynamic>> usersRef = db.collection('users');
    if (countryFilter != null && countryFilter.isNotEmpty) {
      usersRef = usersRef.where('country', isEqualTo: countryFilter);
    }
    if (friendUids != null && friendUids.isNotEmpty) {
      usersRef = usersRef.where(FieldPath.documentId, whereIn: friendUids);
    }
    final querySnapshot = await usersRef
        .orderBy('ecopoints', descending: true)
        .limit(limit)
        .get();
    return querySnapshot.docs
        .map((doc) => UserModel.fromFirestore(doc))
        .toList();
  } catch (e) {
    AppLogger.error('Error reading users for leaderboard: $e');
    return [];
  }
}
```

Figure 5. Screenshot of code 2

This code is responsible for fetching and displaying the leaderboard from the Firebase backend. The function readUsersSortedByEcopoints runs whenever a user navigates to the community or leaderboard page, accepting parameters to filter the results by country or to a specific list of friends.

The process begins by creating a base query reference, usersRef, which points to the users collection in the Firestore database. This initial reference represents all users in the system. The code then uses dynamic query building to conditionally apply filters. If a countryFilter is provided, a where clause is added to the query to only include users from that specific country. Similarly, if a list of friendUids is passed, another where clause filters the results to only include users whose document IDs are in that list. This approach is highly efficient, as it allows one function to serve multiple leaderboard views (e.g., Global, National, Friends).

After building the query, the code chains on the final logic. The .orderBy('ecopoints', descending: true) method instructs the Firebase server to sort the filtered users by their points from highest to lowest. The .limit(limit) method then optimizes performance by telling the server to only retrieve the top 50 users, preventing unnecessary data transfer. The .get() method executes the complete query on the server. Firebase handles all the complex filtering and sorting, sending back only the requested documents. Finally, the code maps this list of raw documents into structured UserModel objects, which the app's UI can easily use for display. The catch block ensures any database errors are logged without crashing the app.

The mobile client's purpose is to provide an intuitive and responsive user interface (UI). Implemented using a cross-platform framework, this component relies on the principles of User Experience (UX) Design to ensure a seamless journey. It functions as the visual layer of the app, displaying data from the Firebase backend (like leaderboards) and capturing user input (like photos) to send to the Gemini AI engine for processing.

Figure 6. Screenshot of home page

```
final ThemeData lightTheme = ThemeData(
  brightness: Brightness.light,
  colorScheme: const ColorScheme.light(
    primary: Color(0xFF2e7d32), // Deep green
    primaryContainer: Color(0xFFd9f7e5), // Light green background
    secondary: Color(0xFF4db6ac), // Teal accent
    secondaryContainer: Color(0xFFb2f2bb), // Medium green
    surface: Colors.white,
    surfaceContainerHighest: Color(0xFFF1F8E9), // Very light green
    onPrimary: Colors.white,
    onPrimaryContainer: Color(0xFF2e7d32),
    onSecondary: Colors.white,
    onSecondaryContainer: Color(0xFF2e7d32),
    onSurface: Color(0xFF212121),
    onSurfaceVariant: Color(0xFF757575),
    outline: Color(0xFFE0E0E0),
  ),
  fontFamily: 'Roboto',
  appBarTheme: const AppBarTheme(
    backgroundColor: Color(0xFF2e7d32),
    foregroundColor: Colors.white,
    elevation: 0,
    centerTitle: true,
    titleTextStyle: TextStyle(
      fontSize: 20,
      fontWeight: FontWeight.w600,
      fontFamily: 'Roboto',
      color: Colors.white,
    ),
  ),
  textTheme: const TextTheme(
    displayLarge: TextStyle(
      fontSize: 32,
      fontWeight: FontWeight.bold,
      fontFamily: 'Roboto',
      color: Color(0xFF2e7d32),
      height: 1.2,
    ),
    displayMedium: TextStyle(
      fontSize: 28,
      fontWeight: FontWeight.bold,
```

Figure 7. Screenshot of code 3

This code defines the visual theme and styling for the entire EcoWise application, ensuring a consistent and aesthetically pleasing user interface. This lightTheme object runs at the very start of the app's lifecycle, providing a centralized set of design rules that all other UI components inherit. The purpose of this approach is twofold: it ensures brand consistency and drastically improves development efficiency. By defining styles in one place, any future design changes can be made globally with a single edit, rather than hunting down and modifying individual components.

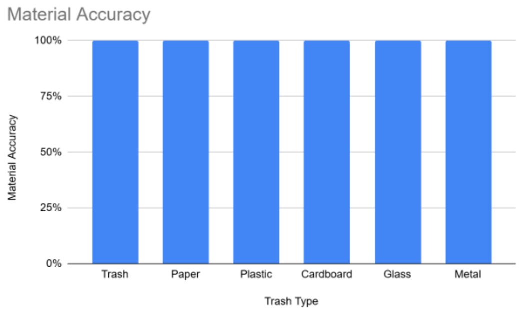
This centralized theme is foundational to good UI/UX, which is critical for an app like EcoWise. A polished, intuitive interface builds user trust and makes the app feel reliable and professional. For a task like waste sorting, which can feel like a chore, a clean and responsive UI makes the process feel effortless and even enjoyable. It establishes a ColorScheme with specific hex codes for primary and secondary colors to create a cohesive green and teal palette. The appBarTheme and textTheme standardize navigation and typography, ensuring every screen feels familiar. This thoughtful design is key to user retention; if the app is easy and pleasant to use, users are far more likely to integrate it into their daily habits and achieve the app's ultimate goal of fostering long-term, sustainable behavior.

4. EXPERIMENT

4.1. Experiment 1

A potential blind spot is the AI’s accuracy with ambiguous items, low resolution images, and images with obscured or confusing orientations. This is critical because the app’s core functionality relies on providing correct disposal guidance.

To test this, we will compile a dataset of images that encompass common recyclables, landfill items, and unclear items. Including difficult images that mirror real-world conditions is crucial to ensuring the app works in most situations, including on a significant number of ambiguous items, such as composite coffee cups, soiled containers, or multi-material packaging. Each image would be labeled with the correct disposal category, creating a ground truth for the experiment. Then, the images will be fed into the classification system, and each output will be recorded. This setup isolates the model's performance, allowing for a direct comparison between its predictions and the verified correct answers.



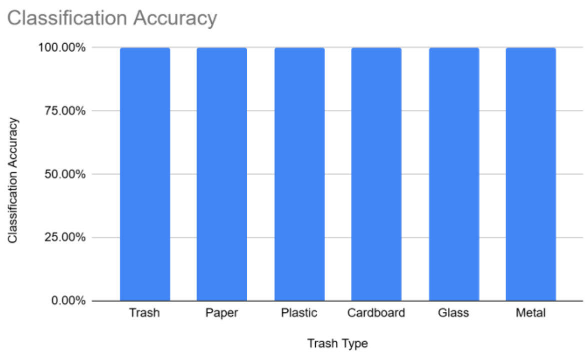


Figure 8. Figure of experiment 1

Our experiment revealed a 100% accuracy rate for both material type and disposal recommendation. As such, the mean, median, highest, and lowest values for accuracy were all uniformly 100%. The result was surprising, as even recent AI models struggle with achieving such flawless image recognition [18]. This result is a reflection of the advanced multimodal capabilities of recent AI models. Unlike simpler, custom-trained models that might struggle with visual nuance, Gemini can understand real-world context with exceptional precision [11][19]. It correctly interpreted varied materials and positions, including multi-material packaging and layered material. This validates its selection as the core engine for Ecowise. This is possible due to Google's generous API limits, allowing free usage of their top models. As pricing models change in the future, the effects on Ecowise might require re-evaluation.

4.2. Experiment 2

A potential blind spot is the reliability of the achievement system. The achievements system is important since bugs that prevent users from earning rewards can undermine motivation and reduce the effectiveness of the app.

To test this, we will experimentally verify the requirements for each achievement and check whether the actions result in the correct achievement being awarded. For each action, I will make sure the achievement shows up for the user to encourage their progress as well as being properly updated in the backend Firestore database. To facilitate this verification, we will utilize several test accounts to achieve certain requirements, such as being added as a friend by multiple users. In addition, this testing will occur over several days to make sure the logic functions properly in all situations. This setup ensures that the logic path in the gamification system is checked against its intended criteria, confirming the system's robustness.

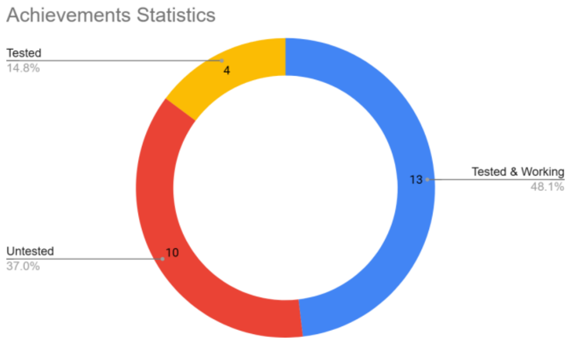


Figure 9. Figure of experiment 2

Our analysis of the 17 tested achievements revealed a success rate of approximately 76.5%, with 13 achievements functioning correctly and 4 failing. The highest value in our test set was a successful validation, and the lowest was a failed test. This result did not meet my initial expectations, as I had anticipated near-perfect backend logic. Upon review, the data indicates that failures were linked to complex achievements with time-based, or multiconditional triggers, such as classifying multiple items within a certain time span. In contrast, simpler, count-based achievements performed well. I believe the biggest factor affecting the results was the complexity of the database logic and maintaining the achievements properly over time. This suggests that while the core system for simple triggers is correct, the more sophisticated gamification elements require further debugging and edge-case handling to ensure they are completely reliable for the users.

5. Related Work

The Recycling Partnership tackles waste contamination through direct, community-level intervention using physical toolkits and educational campaigns [16]. Their solution provides municipalities with resources like information tags for recycling bins and mailers to educate residents on proper sorting. While effective at raising awareness in targeted areas, this method has significant limitations. It is costly to deploy, reliant on physical materials, and its impact is difficult to measure or scale nationally. The approach ignores the user's need for immediate, point-of-decision guidance and fails to provide ongoing engagement. EcoWise improves upon this by offering a free, scalable digital tool that provides instant, AI-powered feedback, making accurate recycling accessible to anyone with a smartphone and fostering long-term habits through gamification [6].

Recycle Coach provides residents with hyper-localized recycling information, such as pickup schedules and sorting guidelines, through a platform licensed by municipalities [13]. This solution is effective for users who need to look up pre-defined rules for their specific area. However, its primary limitation is its dependence on municipal contracts, making it unavailable in countless communities and rural areas that lack funding. The platform ignores the user's critical need to identify an unknown object in real-time. EcoWise improves upon this by offering a universally accessible AI scanner that can classify any item on the spot, combined with a gamification system designed to foster continuous engagement, independent of local government partnership.

The Recycle Smart MA initiative is a public education campaign that uses an informational website, and a search tool called the "Recyclopedia" [10]. Users can manually look up items to see local disposal guidelines for Massachusetts. While this provides accurate, localized data, its effectiveness is limited. The system is passive, requiring users to know what to search for, and it is geographically restricted, offering no value outside its service area. It also lacks any mechanism for user engagement or habit formation. EcoWise improves upon this by providing an active, AI-powered scanner that works universally, removing the burden of manual searching and providing instant, on-the-spot classification for any item, anywhere in the world.

6. CONCLUSIONS

A primary limitation of EcoWise is its dependence on an internet connection for both AI classification and database synchronization, which restricts its usability in rural or low-connectivity areas. Additionally, while the app can identify a material like "PET plastic," it cannot currently account for hyper-local recycling rules, which vary significantly by municipality [4].

To improve this, two key features are necessary. First, I would implement offline functionality by embedding a lightweight, on-device TensorFlow Lite model to classify common items without a network connection, escalating only ambiguous scans to the Gemini API [7]. Second, I would integrate a location-based system. With user permission, the app could use the device's location to fetch specific local recycling ordinances from a database of municipal regulations. This would allow EcoWise to provide precise, actionable guidance for things like "Recyclable in your area, but remove the cap", making it a truly comprehensive and reliable sustainability tool.

Ecowise successfully demonstrates how advanced technology can address critical environmental challenges. By integrating artificial intelligence with a gamified mobile platform, it transforms waste sorting from a confusing chore into an engaging, educational experience. This project serves as proof of concept for a scalable, low-cost solution to promote global sustainability.

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