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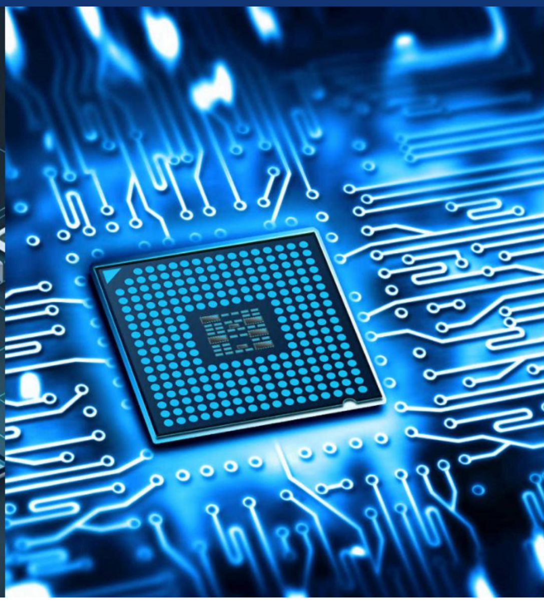

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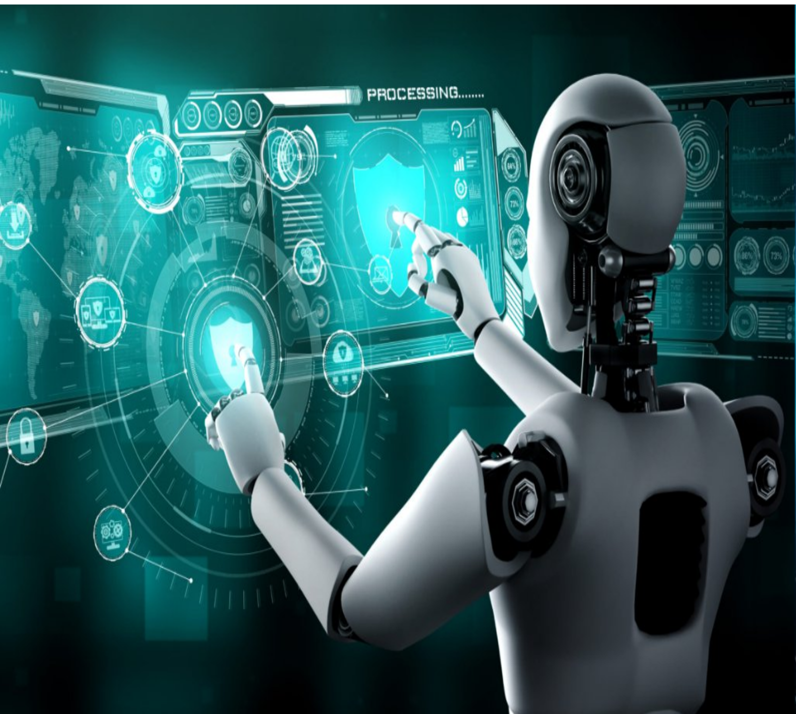

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ReHarvest.AI: A Multimodal Deep Learning and Smart Routing Framework for Sustainable Fruit Waste Reduction

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ABSTRACT: Fruit waste, particularly in the fruit supply chain, poses a significant challenge to sustainability, contributing to economic losses and environmental degradation. Inefficient identification of fruit spoilage stages and lack of timely redistribution mechanisms often result in large quantities of edible fruit being discarded. This paper presents ReHarvest.AI, an intelligent fruit waste management and redistribution system designed to minimize waste through real-time decision-making and deep learning techniques.The proposed system utilizes a Convolutional Neural Network (CNN)-based model to classify fruits into multiple spoilage stages, including fresh, near spoilage, and spoiled, enabling accurate assessment of fruit quality. In addition, the system incorporates a predictive module to estimate remaining shelf life using environmental and temporal data. Based on these insights, a smart routing engine dynamically directs consumable fruits to non-governmental organizations (NGOs) for donation, while spoiled fruits are redirected to composting or biogas production units.ReHarvest.AI further integrates real-time inventory monitoring, logistics optimization, and stakeholder coordination through a cloud-based architecture. The platform provides role-based dashboards, live tracking of pickups, and automated alerts to ensure timely action and reduce delays in redistribution. An analytics module evaluates key performance indicators such as waste reduction, donation efficiency, and environmental impact, including CO_2 emission savings.The system is implemented using a scalable architecture with a React-based frontend, Spring Boot backend, and PostgreSQL database, ensuring efficient performance across web platforms. Experimental results demonstrate improved accuracy in spoilage detection and a significant reduction in fruit waste through optimized redistribution strategies.The proposed solution contributes to sustainable supply chain management by combining artificial intelligence, real-time analytics, and collaborative logistics, ultimately supporting communities, reducing environmental impact, and promoting responsible resource utilization.

KEYWORDS: Fruit Waste Reduction, Artificial Intelligence, Spoilage Classification, Predictive Analytics, Smart Supply Chain, Waste-to-Resource, Real-Time Monitoring.

I. INTRODUCTION

Fruit waste, particularly in the fruit supply chain, has emerged as a critical global challenge, contributing significantly to economic losses, environmental degradation, and fruit insecurity. A large proportion of fruits are discarded due to improper handling, lack of timely identification of spoilage stages, and inefficient redistribution mechanisms. Traditional waste management practices rely heavily on manual inspection and static decision-making processes, which are often inaccurate, time-consuming, and incapable of responding to real-time conditions. These limitations highlight the urgent need for intelligent systems that can optimize fruit utilization and minimize waste through data-driven approaches.

ReHarvest.AI is an AI-driven platform designed to address these challenges by integrating deep learning, real-time data processing, and smart logistics management. The proposed system enables automatic classification of fruits based on their freshness levels—fresh, near spoilage, and spoiled—using advanced image-processing techniques. Additionally, the system incorporates predictive analytics to estimate the remaining shelf life of fruits by analyzing environmental factors such as storage conditions, temperature, and time. This enables proactive decision-making to prevent unnecessary waste.

Beyond spoilage detection, ReHarvest.AI features a smart routing engine that dynamically directs fruits to appropriate channels. Consumable fruits nearing spoilage are efficiently redistributed to non-governmental organizations (NGOs) for donation, while spoiled fruits are redirected to composting or biogas production units. The platform also provides real-time alerts, live tracking of pickups, and role-based dashboards for stakeholders including shopkeepers, collectors, NGOs, and processing units, ensuring seamless coordination across the supply chain.

Furthermore, ReHarvest.AI incorporates analytics and monitoring tools to evaluate key performance indicators such as waste reduction, donation efficiency, and environmental impact, including carbon emission savings. Its scalable architecture supports deployment across web and mobile platforms, ensuring accessibility for diverse users. By combining artificial intelligence, automation, and collaborative logistics, ReHarvest.AI offers a sustainable and efficient solution to fruit waste management, ultimately promoting resource optimization, environmental responsibility, and community support.

II. RELATED WORK

Recent advancements in artificial intelligence, computer vision, and smart logistics systems have significantly contributed to the development of intelligent solutions for fruit waste reduction. Existing research primarily focuses on three key areas: waste classification, reverse logistics and routing, and real-time monitoring systems.

AI-driven classification systems have been widely used to categorize fruit waste based on freshness and spoilage levels. Deep learning models, particularly Convolutional Neural Networks (CNNs), have demonstrated high accuracy in identifying visual features associated with fruit quality. Several studies report the use of architectures such as VGG-19 and other image-based models achieving high precision in distinguishing organic waste, including fruits, from non-organic materials. These systems enable automated sorting and form the foundation for intelligent fruit classification, similar to the Fresh, Near Spoilage, and Spoiled categorization used in ReHarvest.AI.

In parallel, research in reverse logistics and supply chain optimization has explored the use of machine learning and IoT-based systems to manage perishable goods efficiently. Dynamic routing models leverage real-time data such as inventory status, environmental conditions, and shelf-life predictions to optimize redistribution pathways. These approaches aim to minimize fruit waste by directing consumable items to donation channels while diverting unusable waste to composting or energy recovery systems. Such frameworks closely align with the smart routing engine proposed in ReHarvest.AI, which integrates classification outcomes with logistics decision-making.

Real-time monitoring and mobile-based applications have also gained prominence in reducing fruit waste. Several systems provide spoilage detection, ripeness estimation, and user notifications to enable timely consumption or redistribution. These applications often incorporate image processing and predictive analytics to support decision-making at both household and commercial levels. Additionally, advancements in post-harvest management systems use AI to monitor fruit maturity and quality during storage and transportation, reducing losses across the supply chain.

Beyond individual components, comprehensive waste management platforms have been developed to integrate analytics, stakeholder interaction, and sustainability tracking. These systems typically include dashboards for monitoring key performance indicators such as waste reduction, carbon emission savings, and operational efficiency. Role-based access and cloud-based architectures further enhance scalability and usability across multiple stakeholders, including retailers, NGOs, and processing units.

Despite these advancements, existing solutions often operate in isolation, focusing either on classification, logistics, or monitoring. ReHarvest.AI addresses this gap by integrating deep learning-based spoilage detection, real-time data analysis, and intelligent routing into a unified platform. By combining classification, redistribution, stakeholder collaboration, and impact analytics, the proposed system offers a comprehensive approach to fruit waste management, promoting sustainability and efficient resource utilization.

III. PROPOSED ALGORITHM

The proposed ReHarvest.AI system is designed to intelligently manage fruit waste using machine learning, real-time data analysis, and smart routing strategies. The system integrates image processing, deep learning–based spoilage detection, environmental data analysis, and automated decision-making to optimize fruit utilization and reduce waste.

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The algorithm is divided into multiple modules including image acquisition, spoilage detection, shelf-life prediction, smart routing, and cloud-based data management. These modules work together to provide real-time monitoring and efficient redistribution of fruits.

3.1 Image Acquisition and Pre-Processing

The first stage of the system involves capturing fruit images through a mobile or web interface by shopkeepers or collectors. The captured image is preprocessed before being passed to the machine learning model.
The preprocessing stage includes:
* Converting the image to RGB format
* Resizing the image to 224 × 224 pixels
* Normalizing pixel values for improved model performance
The processed image is then converted into tensor format suitable for CNN inference.

$$Ip = Normalize(Resize(I, 224 \times 224))$$

Where:
I = input fruit image
Ip = processed image
This step ensures uniformity and consistency across all input images.

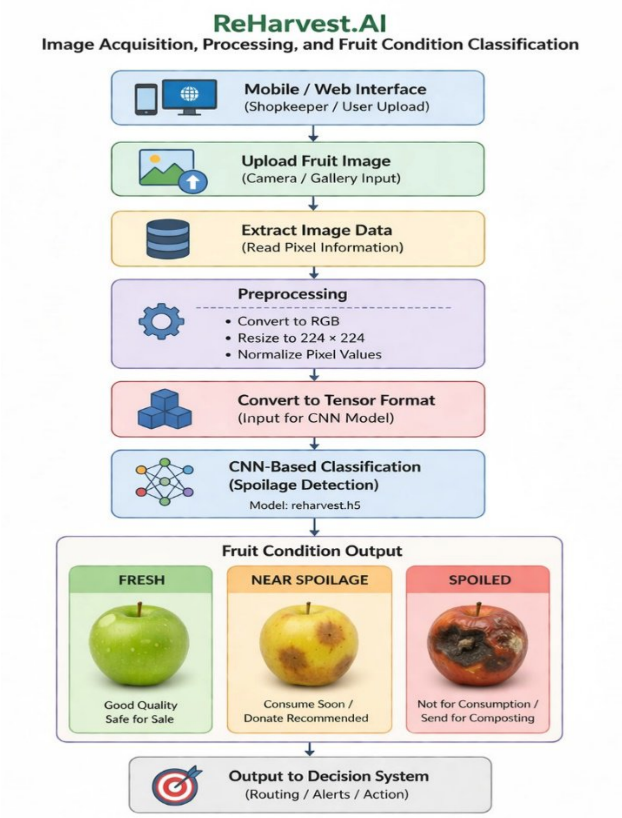

Fig. 3.1.1. Image Acquisition and CNN-Based Spoilage Detection Workflow

3.2 CNN-Based Spoilage Detection

After preprocessing, the image is passed to a trained Convolutional Neural Network (CNN) model (reharvest.h5). The model extracts visual features such as texture, color variation, and surface defects to classify fruit condition.
The output is a probability vector indicating the likelihood of each class:
* Fresh
* Near Spoilage

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* Spoiled

The final classification is obtained by selecting the class with the highest probability.

$$C=\arg\max(CNN(I_p))$$

Where:
CNN = trained deep learning model
C = predicted fruit condition
The model also generates a confidence score indicating prediction reliability.

3.3 Shelf-Life Prediction and Environmental Analysis

To enhance decision-making, the system integrates environmental and temporal data to estimate the remaining shelf life of fruits.

The parameters considered include:
* Temperature
* Humidity
* Storage duration

These factors are used to compute the spoilage risk and remaining usable time.

$$S=f(T,H,t)$$

Where:
T = temperature
H = humidity
t = storage time
S = estimated shelf life
This module enables proactive identification of fruits that are likely to spoil soon.

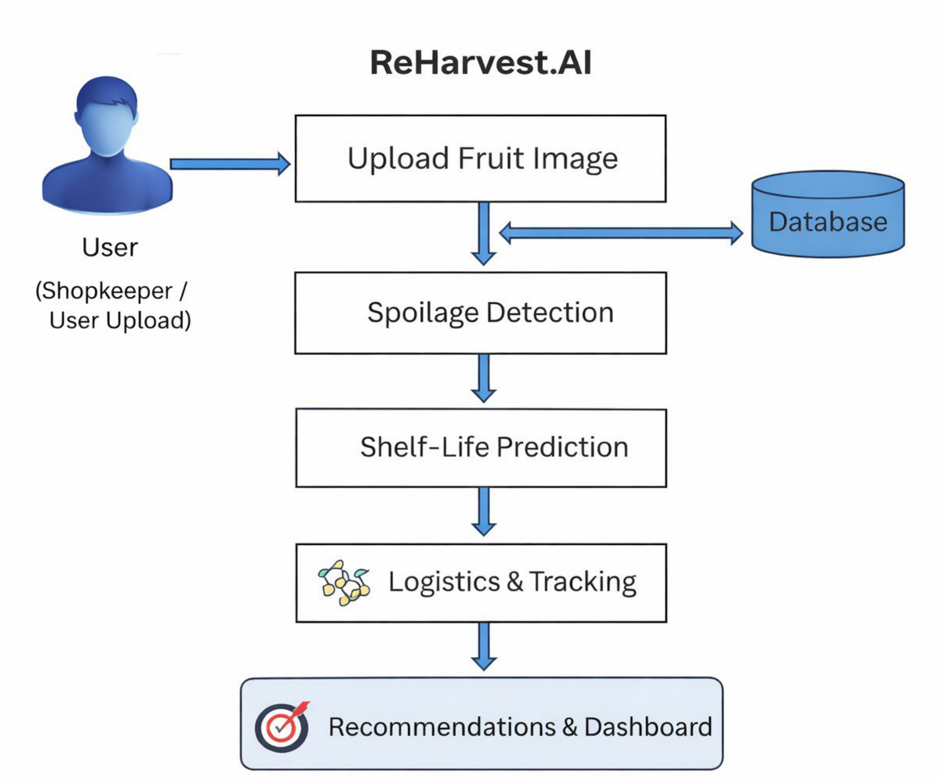

Fig. 3.3.1: ReHarvest.AI system architecture for intelligent fruit waste management.

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3.4 AI-Based Decision and Routing Mechanism

Based on the classification and shelf-life prediction, the system determines the optimal action using a rule-based decision engine.

* If fruit is Fresh → Retain for sale
* If Near Spoilage and shelf-life below threshold → Route for donation
* If Spoiled → Route for composting or biogas production

The smart routing system then assigns the appropriate destination by analyzing:

* Distance to NGOs or compost units
* Availability of collectors
* Urgency based on spoilage level

This ensures efficient and timely redistribution of fruits.

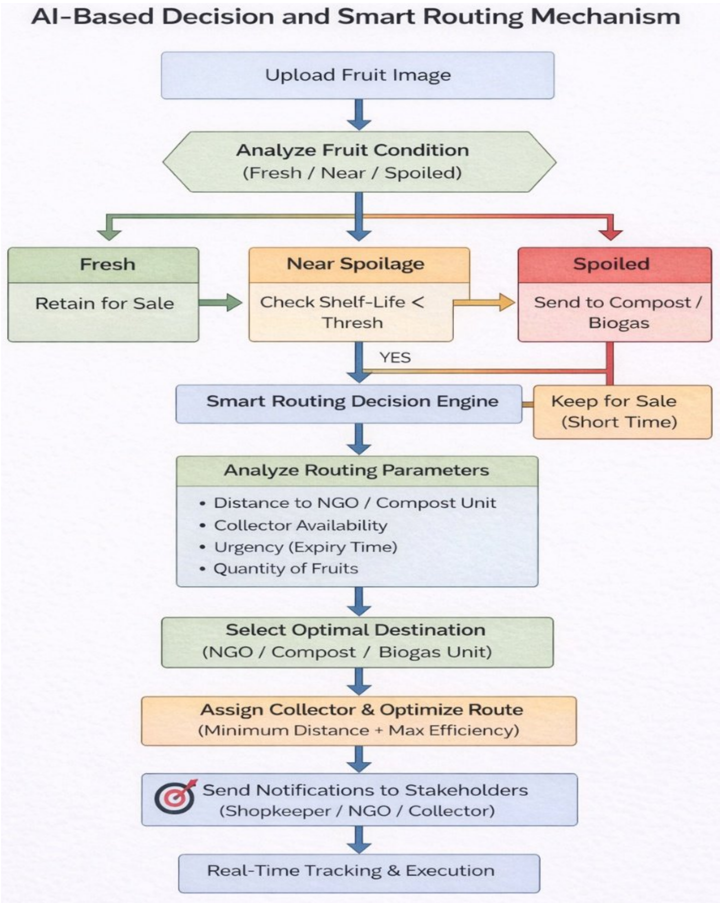

Fig. 3.4.1: Smart routing and decision-making workflow for fruit waste management in ReHarvest.AI.

3.5 Cloud Data Management and Dashboard Integration

All system data, including predictions, inventory status, routing logs, and user interactions, are stored in a cloud-based database (Supabase).

The dashboard module provides:

* Waste classification statistics
* Donation and composting metrics
* Real-time tracking of pickups
* Environmental impact (CO_2 reduction, food saved)

This enables stakeholders to monitor system performance and make data-driven decisions.

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3.6 Pseudocode of Proposed Algorithm

```
Step 1: Initialize system components
        Load CNN model (reharvest.h5)
        Initialize database and APIs
Step 2: Capture or upload fruit image
Step 3: Preprocess image
        Convert to RGB
        Resize to 224 × 224
        Normalize pixel values
Step 4: Classify fruit condition using CNN
        Class ← Predict(image)
Step 5: Collect environmental data
        Temperature, Humidity, Time
Step 6: Estimate shelf life
        Shelf_Life ← Predict(T, H, t)
Step 7: Decision making
        IF Class = Fresh:
            Action ← Store for sale
 ELSE IF Class = Near Spoilage AND Shelf_Life < Threshold:
Action ← Donate to NGO
        ELSE:
            Action ← Send to composting
Step 8: Optimize routing and assign collector
Step 9: Store results in database
Step 10: Display output on dashboard
```

IV. SIMULATION RESULTS

The ReHarvest.AI system was evaluated through functional testing and user interface validation using the developed web-based prototype. The results demonstrate successful implementation of fruit waste classification, smart routing, and stakeholder interaction through an intuitive and responsive interface. ReHarvest.AI demonstrates an integrated fruit waste management workflow that connects waste logging, freshness assessment, routing decisions, logistics coordination, and impact monitoring across multiple user roles. The platform supports automatic handling of fruit waste based on its condition and ensures that each stakeholder receives the right information and action at the right time.

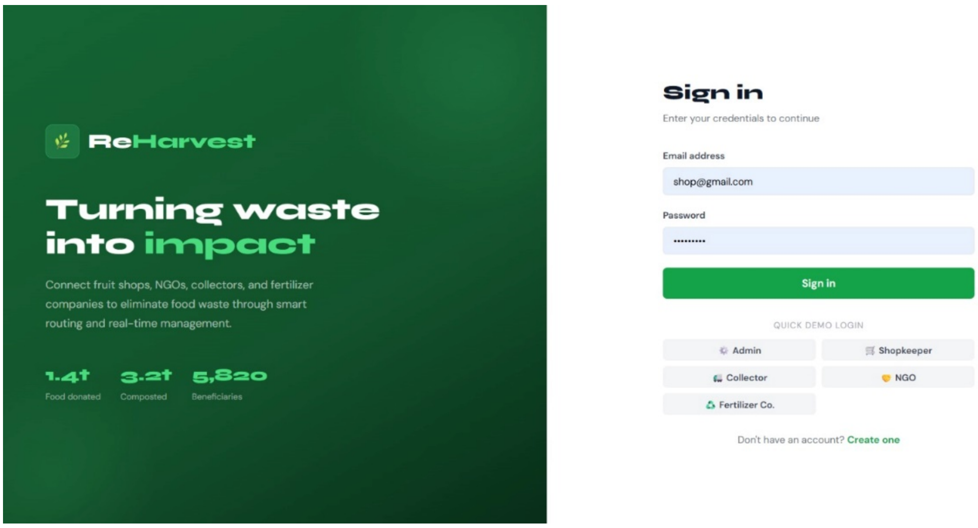

Fig.4.1. Reharvest.AI system login page

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The admin module provides a consolidated overview of the entire system, allowing supervisors to monitor total waste handled, donation activity, fertilizer diversion, delivery progress, and overall environmental impact. It also offers weekly trend views and pickup activity tracking, which help administrators understand system performance and operational movement over time.

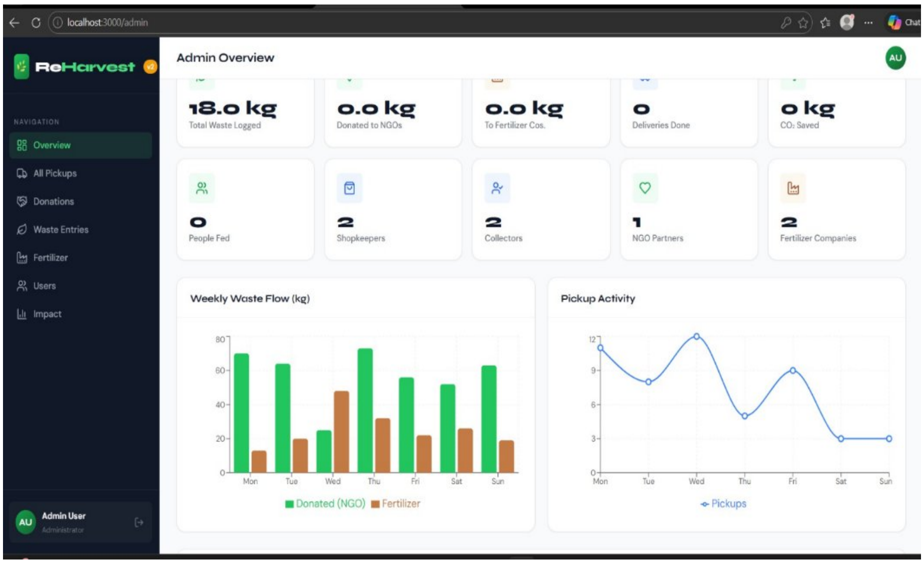

Fig.4.2. Admin dashboard overview

The shopkeeper module allows users to log fruit waste and identify its freshness status as fresh, near spoilage, or spoiled. Based on this classification, the system recommends the appropriate route, helping users quickly decide whether the fruit should be sent for donation or composting. It also includes a reward mechanism that encourages responsible waste reporting and participation.

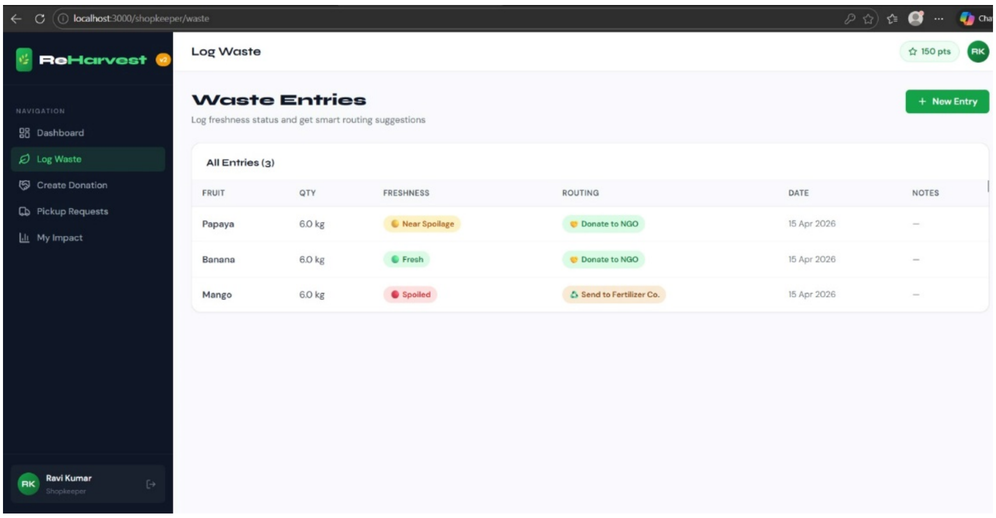

Fig.4.3. Shopkeeper impact dashboard.

The collector module manages pickup assignments and delivery coordination. It shows active jobs, available tasks, and delivery status, enabling collectors to accept assignments and complete transportation efficiently. This improves logistics flow and reduces delays in moving waste from the source to the destination.

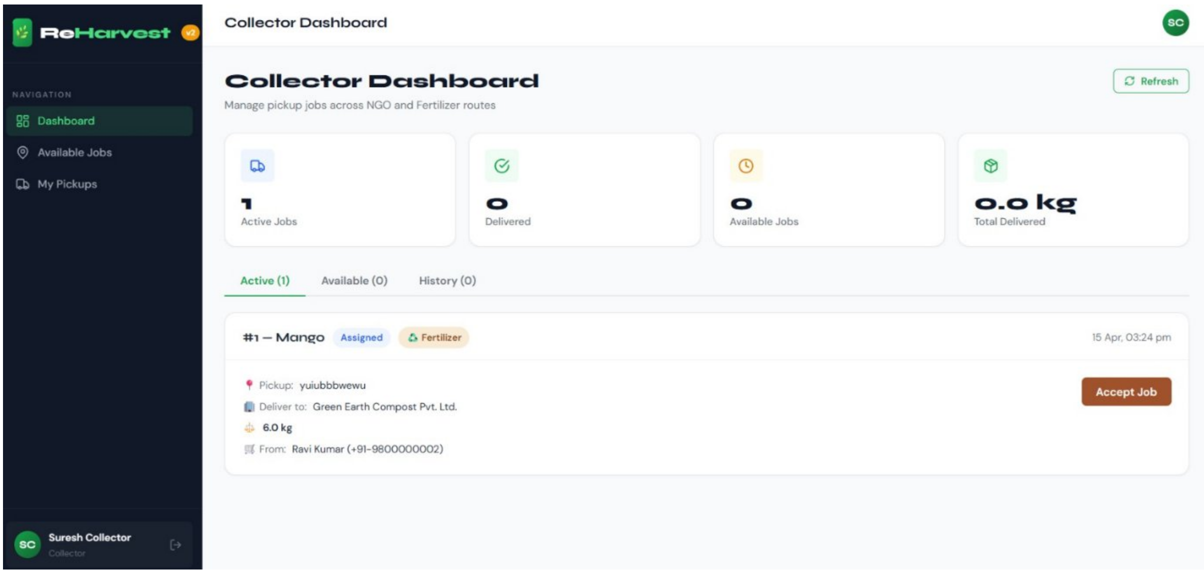

Fig.4.4.Collector pickup dashboard.

The NGO module supports donation handling by listing available fruit donations and allowing partners to accept or decline them. It helps NGOs identify edible surplus food in time and coordinate with collectors for timely receipt. This strengthens food redistribution and improves the usability of donated produce.

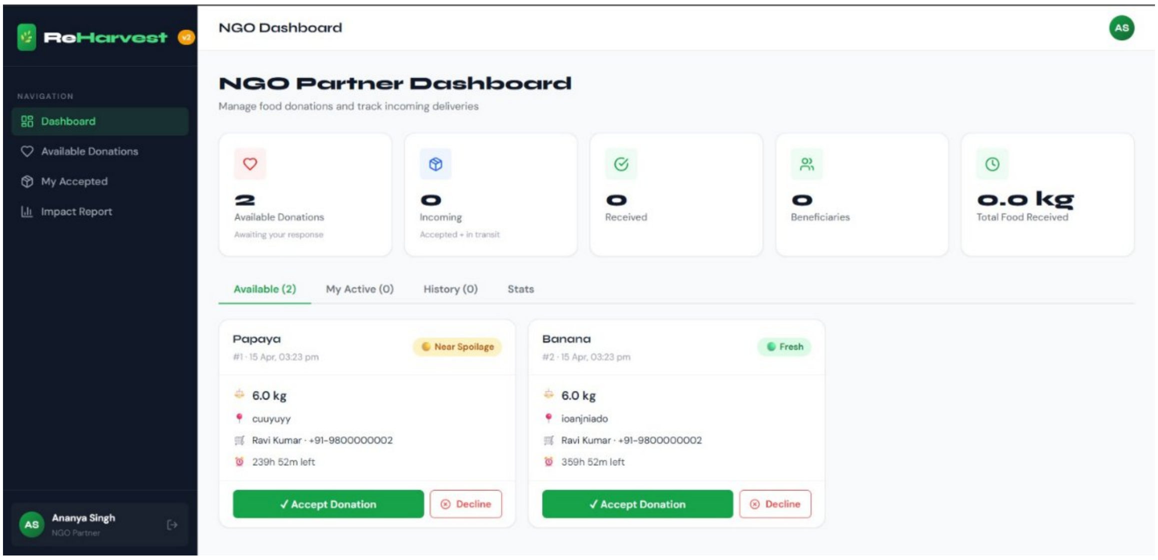

Fig.4.5.NGO donation dashboard.

The fertilizer company module manages incoming spoiled waste for composting or other fertilizer-related processing. It provides visibility into processing capacity, pending deliveries, and compost output trends, which supports operational planning and resource utilization. This module ensures that spoiled waste is redirected away from landfill and used in a productive circular process.

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The authentication and role-based interface structure improves security and usability by giving each user type access only to the features relevant to their work. Overall, the system functions as a multi-stakeholder platform that combines classification, routing, logistics, analytics, and sustainability support in one workflow.

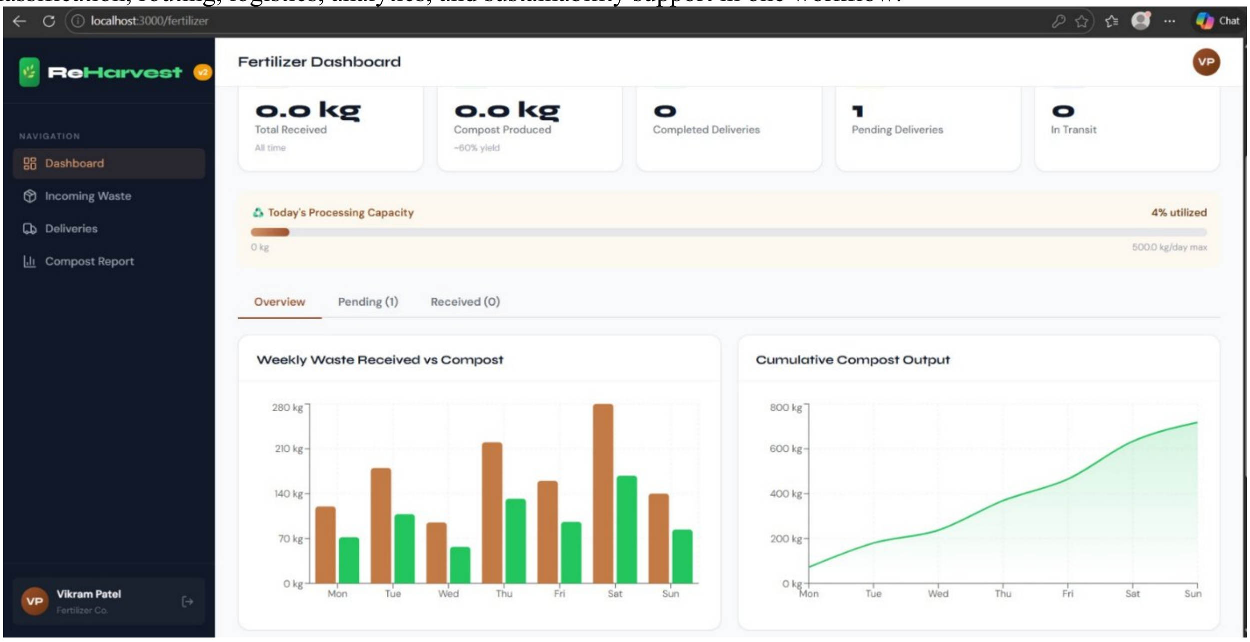

Fig.4.6. Fertilizer processing dashboard.

V. CONCLUSION AND FUTURE SCOPE

ReHarvest.AI provides a comprehensive and intelligent solution for fruit waste management by integrating AI-based spoilage detection, predictive analytics, and a user-friendly interface. The system accurately classifies fruits into fresh, near spoilage, and spoiled categories using image analysis, enabling timely decision-making and reducing unnecessary waste. By incorporating environmental factors and shelf-life prediction, the platform offers deeper insights into fruit quality and supports efficient resource utilization through an interactive dashboard.

The system enhances operational efficiency through features such as smart routing, real-time pickup tracking, and automated donation workflows. Its cloud-based architecture and modular design ensure scalability, reliability, and seamless interaction among multiple stakeholders including shopkeepers, NGOs, collectors, and processing units. Additionally, the platform promotes sustainability by reducing landfill waste, lowering carbon emissions, and supporting food redistribution to communities in need. Overall, ReHarvest.AI demonstrates the potential of artificial intelligence in transforming traditional waste management systems into smart, data-driven, and environmentally responsible solutions.

In the future, the system can be further improved by incorporating larger and more diverse datasets covering multiple fruit types and real-world storage conditions to enhance model accuracy and robustness. Integration with IoT sensors for monitoring temperature, humidity, and storage environments can provide more precise shelf-life predictions. Advanced optimization techniques such as machine learning–based routing or reinforcement learning can be applied to improve logistics efficiency at scale.

Further developments such as mobile application deployment, offline functionality for low-connectivity regions, multilingual support, and integration with government food distribution systems can significantly expand the platform's reach and usability. Additionally, incorporating blockchain-based tracking for transparent donation processes and advanced analytics for predicting waste trends can transform ReHarvest.AI into a fully scalable and globally impactful solution for sustainable food waste management.

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