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Food Waste Intelligence: A Predictive-Prescriptive Machine Learning Framework for Food Waste Reduction and Surplus Donation Analysis

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Abstract: ***Food waste is a major environmental, economic, and social challenge, particularly in food-service environments where inaccurate demand estimation can lead to excessive food preparation and unnecessary waste. This study proposes a predictive-prescriptive machine learning framework for food waste reduction and surplus donation analysis to support data-driven food management decisions. The proposed framework uses historical food, demand, preparation, consumption, and waste data to develop machine learning models for predicting expected food waste. It further incorporates what-if scenario analysis to evaluate different food preparation levels and identify their potential impact on waste and demand coverage. Based on the scenario outcomes, the framework provides a suitable waste-reduction scenario recommendation. It also estimates potential surplus food and performs donation potential analysis to identify food that may be considered for redistribution, subject to appropriate food safety and quality conditions. A web-based application is proposed to present waste predictions, scenario comparisons, recommendations, and surplus insights. The framework integrates prediction, scenario evaluation, recommendation, surplus estimation, and donation analysis into a unified decision-support system aimed at supporting responsible food management and contributing to Sustainable Development Goal 12.***

Keywords: ***Food Waste, Machine Learning, Predictive Analytics, What-If Analysis, Surplus Food.***

I. INTRODUCTION

Food waste is a major environmental, economic, and social challenge. In food service environments, inaccurate demand estimation can lead to excessive food preparation, resulting in unnecessary waste and resource loss. Traditional preparation decisions often rely on previous experience or historical demand, which may not always reflect actual consumption patterns. Machine learning can analyze historical food, demand, preparation, consumption, and waste data to predict expected food waste. However, prediction alone does not indicate which preparation level should be considered. Therefore, the proposed framework combines food-waste prediction with what-if scenario analysis to evaluate different preparation levels and provide a suitable waste-reduction scenario recommendation. The framework also estimates potential surplus food and performs donation potential analysis. A web-based application is used to present predictions, scenario comparisons, recommendations, and surplus insights. The proposed approach aims to support data-driven food-management decisions and contribute to Sustainable Development Goal 12: Responsible Consumption and Production.

II. LITERATURE SURVEY

Food waste has received increasing attention as a major environmental, economic, and social challenge, leading researchers to explore machine learning, digital technologies, demand forecasting, and surplus-food redistribution as potential solutions. Recent studies demonstrate that data-driven approaches can improve demand estimation, support food-waste prevention, and facilitate the redistribution of surplus food. However, these approaches often focus on individual stages of food management rather than providing an integrated framework that connects prediction, preparation decisions, scenario evaluation, and surplus analysis.

Trevisan and Formentini [1] examined the use of digital technologies for food loss and waste prevention and reduction across agri-food supply chains. Their systematic literature review analyzed the adoption of Industry 4.0 technologies and identified research opportunities related to digitalization, sustainability, governance, and implementation. The study highlights the potential of digital technologies for improving food-waste management; however, it primarily provides a review and research agenda rather than implementing a machine-learning-based system for food-waste prediction and preparation decisions.

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Hübner et al. [2] investigated machine-learning-based demand forecasting against food waste through a bakery case study. Their work examined a machine-learning forecasting service and evaluated its environmental impacts and benefits associated with reducing bakery returns. The study demonstrates that improved forecasting can contribute to reducing overproduction and its environmental effects. However, the work mainly focuses on demand forecasting and environmental assessment rather than integrating food-waste prediction with preparation scenario analysis and recommendation.

Rodrigues et al. [3] developed machine learning models for short-term demand forecasting in food catering services to reduce food waste. Their study used real daily data from three catering services and compared machine-learning forecasts with existing demand-estimation approaches. The results demonstrated the potential of machine learning to reduce wasted meals while also improving demand fulfillment. However, the study primarily addresses demand forecasting and does not provide an integrated workflow for evaluating alternative preparation levels, recommending a scenario, and analyzing potential surplus for donation.

Devaraj and Balasubramanian [4] investigated the redistribution of surplus food in the hospitality sector through food donation systems. Their study examined the role of food donation systems in reducing food waste and explored challenges associated with implementing surplus-food redistribution. The research emphasizes the importance of donation and redistribution as sustainable food-management strategies. However, its primary focus is on the redistribution stage and does not combine machine-learning-based prediction with preparation planning and scenario-based waste reduction.

Talwar et al. [5] examined why hospitality and food-service businesses use food-sharing platforms for surplus-food redistribution. Their study used qualitative research with hospitality and food-service professionals and identified factors influencing the adoption and continued use of food-sharing platforms. The research also proposed an assessment, implementation, optimization, and outcomes framework for improving food-sharing practices. However, the focus remains on digital surplus redistribution rather than integrating food-waste prediction, preparation scenario evaluation, and scenario recommendation.

These studies demonstrate the importance of machine learning, demand forecasting, digital technologies, and surplus-food redistribution in addressing food waste. However, existing approaches generally address prediction, waste reduction, or redistribution as separate components. This highlights an opportunity for an integrated decision-support framework that connects food-waste prediction, What-If preparation scenario analysis, scenario recommendation, potential surplus estimation, and donation potential analysis. The proposed framework addresses this opportunity by combining these components into a unified workflow designed to support data-driven food-management decisions in food-service environments.

III. PROBLEM STATEMENT

The food-service sector currently faces challenges in accurately estimating food demand and controlling food waste. Many existing approaches focus on individual activities such as demand forecasting, waste monitoring, or surplus-food redistribution rather than addressing these activities through a unified decision-support framework. This separation limits the ability of food-service organizations to understand expected waste, evaluate alternative preparation levels, and identify potential surplus in a structured and coordinated manner. To overcome these challenges, the proposed Predictive-Prescriptive Machine Learning Framework for Food Waste Reduction and Surplus Donation Analysis integrates food-waste prediction, What-If scenario analysis, preparation scenario recommendation, potential surplus estimation, and donation analysis within a single framework. The system uses historical food, demand, preparation, consumption, and waste data to develop machine learning models for predicting expected food waste. It further evaluates different food-preparation scenarios to understand their potential effect on waste and demand coverage.

The primary objectives of the proposed framework include developing machine learning models for food-waste prediction, identifying relevant patterns associated with waste generation, and evaluating alternative preparation levels through What-If analysis. Based on the scenario outcomes, the framework provides a suitable waste-reduction scenario recommendation. It also estimates potential surplus food and analyzes its potential for donation or redistribution, subject to appropriate food-safety and quality requirements. Finally, a web-based application is developed to present predictions, scenario comparisons, recommendations, and food-waste insights in an interactive manner.

IV. PROPOSED METHODOLOGY

The proposed Food Waste Intelligence framework is developed following a predictive-prescriptive and modular methodology aimed at reducing unnecessary food waste and supporting better food-preparation decisions in food-service environments. The methodology integrates historical food, demand, preparation, consumption, and waste data with machine learning, What-If analysis, scenario-based recommendation, potential surplus estimation, and potential donation analysis. The system is designed to move beyond conventional food-waste monitoring by combining prediction with decision support in a single integrated framework.

The methodology begins with the collection and preparation of historical food-service data containing attributes such as food item, food category, day of the week, weekend and special-event indicators, temperature, customer count, expected demand, preparation quantity, consumption quantity, and waste quantity. The collected data is processed to handle numerical and categorical attributes and is transformed into a suitable format for machine learning. Feature engineering is performed to represent operational and demand-related factors that may influence food waste. The prepared dataset is then divided into training and testing subsets for developing and evaluating the prediction models. The predictive component of the framework formulates food-waste estimation as a regression problem. Machine learning algorithms including Random Forest Regression and Gradient Boosting Regression are trained to estimate the expected quantity of food waste in kilograms. The models are evaluated using Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and coefficient of determination (R^2). Based on the implemented model comparison, the Random Forest model is selected as the production model for subsequent analysis. This prediction component provides the foundation for the decision-support stages of the framework. A key feature of the proposed system is its What-If preparation scenario analysis. Instead of considering only a single preparation quantity, the system evaluates alternative preparation levels around the baseline quantity. Different scenarios, such as 80%, 90%, 100%, 110%, and 120% of the baseline preparation, are analyzed to determine their corresponding predicted waste and demand coverage. This enables the system to examine the trade-off between insufficient preparation and excessive preparation and provides a quantitative basis for comparing alternative food-preparation decisions. The framework further incorporates a prescriptive recommendation module that identifies a suitable preparation scenario from the evaluated alternatives. The recommendation considers demand coverage together with predicted waste so that a scenario with lower waste is not selected when it may result in insufficient food availability. The system therefore uses the What-If results to identify a feasible preparation level that can reduce unnecessary waste while maintaining adequate demand coverage. This stage transforms the output of predictive analytics into an actionable preparation recommendation.

Following scenario recommendation, the system estimates the potential surplus food associated with the selected preparation scenario. The potential surplus is subsequently analyzed to determine its potential for donation or redistribution. The system presents potential donation quantities as analytical estimates rather than treating all surplus food as automatically suitable for donation. Actual redistribution would depend on appropriate food-safety, quality, storage, and handling conditions. This enables the framework to connect food-waste reduction with potential surplus recovery. The complete methodology is implemented through a modular web-based application named Food Waste Intelligence. The application provides dedicated modules for historical dashboard analysis, food-waste prediction, What-If scenario analysis, surplus and donation analysis, model evaluation, and live end-to-end analysis. The live analysis module integrates the complete workflow by accepting operational inputs, generating a waste prediction, evaluating alternative preparation scenarios, recommending a suitable preparation quantity, and estimating potential surplus and donation. The system also maintains separation between the historical training dataset and newly generated live prediction records to preserve the integrity of model training and evaluation. The proposed architecture therefore integrates Predictive Analytics and Prescriptive Analytics into a unified decision-support framework. The overall methodology follows the sequence of historical data preparation, machine learning-based waste prediction, preparation-level scenario analysis, recommendation, potential surplus estimation, and potential donation analysis. The resulting system provides an interactive platform for understanding food-waste patterns and supporting data-driven food-management decisions.

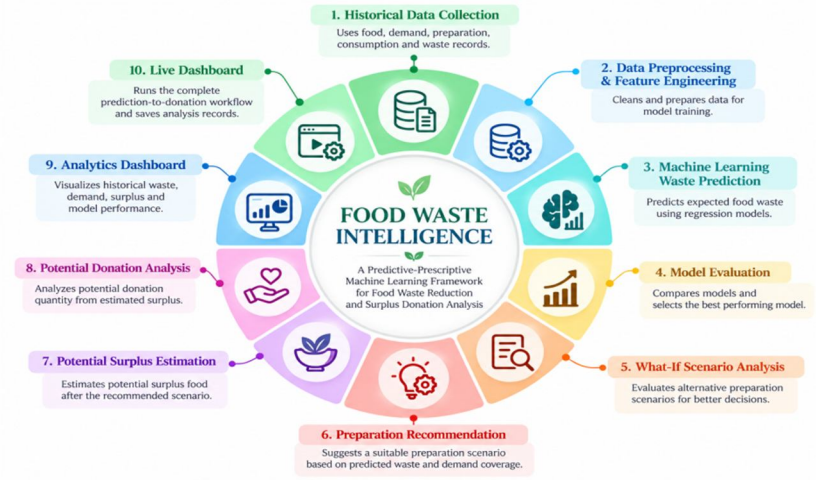


Fig. 1. Core features of the Food Waste Intelligence framework.

V. IMPLEMENTATION

The proposed Food Waste Intelligence framework is implemented as a web-based predictive-prescriptive decision-support system that integrates machine learning, data analytics, scenario evaluation, and surplus-donation analysis. The implementation is organized into modular components so that each stage of the proposed methodology can operate independently while contributing to the overall food-waste management workflow. The system uses Python-based machine learning and backend services together with a web-based frontend for interactive analysis and visualization.

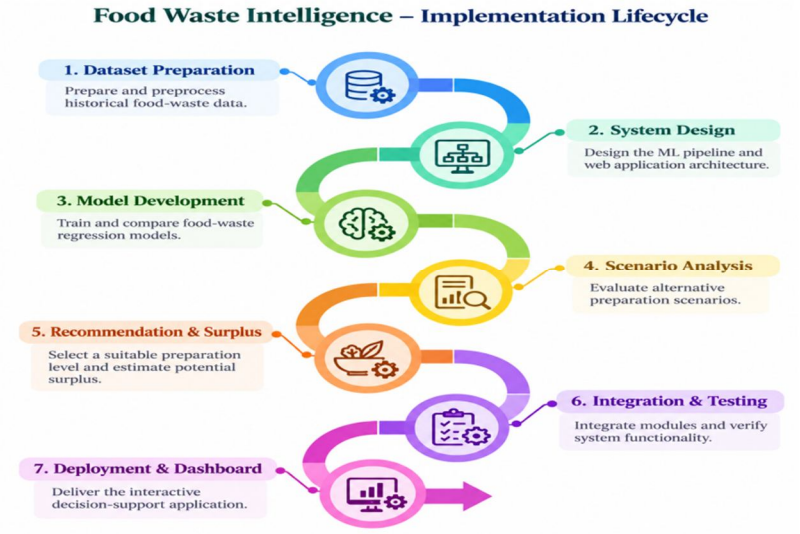


Fig. 2. Development lifecycle of the proposed system.

The historical dataset is stored in a structured CSV format and contains food-service records covering food items, categories, demand, preparation, consumption, environmental conditions, and waste. The implemented dataset contains 5,840 records covering 730 days and eight food items. Python libraries such as Pandas and NumPy are used for data processing, transformation, and analytical operations. Categorical and numerical attributes are prepared through the preprocessing pipeline before being supplied to the machine learning models.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	date	food_item	category	day_of_w	is_weeker	is_special	temperatu	customer_	expected_	preparation	consumption	predicted_waste	potential_surplus_kg	potential_donation_kg	
2	01-01-2024	Biryani	Main Cour	Monday	0	0	24.84	124	45.57	47.16	45.57	0.05	0	0	
3	01-01-2024	Rice	Main Cour	Monday	0	0	24.84	114	28.69	27.48	27.87	1.03	0.75	1.15	
4	01-01-2024	Curry	Main Cour	Monday	0	0	24.84	120	32.37	29.55	27.93	4.97	4.13	2.57	
5	01-01-2024	Dal	Main Cour	Monday	0	0	24.84	112	25.2	20.79	21.03	4.95	4.02	4.16	
6	01-01-2024	Chapati	Main Cour	Monday	0	0	24.84	121	11.25	11.44	11.25	0.05	0	0	
7	01-01-2024	Pasta	Main Cour	Monday	0	0	24.84	108	31.35	29.26	27.95	3.78	3.21	1.9	
8	01-01-2024	Salad	Side	Monday	0	0	24.84	105	16.07	15.13	15.23	1	0.81	0.89	
9	01-01-2024	Dessert	Dessert	Monday	0	0	24.84	107	14.53	13.85	13.34	1.31	1.15	0.61	
10	02-01-2024	Biryani	Main Cour	Tuesday	0	0	29.27	118	50.72	44.59	44.7	7.11	5.63	5.77	
11	02-01-2024	Rice	Main Cour	Tuesday	0	0	29.27	111	28.05	24.88	24.33	4.25	3.42	2.95	
12	02-01-2024	Curry	Main Cour	Tuesday	0	0	29.27	116	33.57	30.61	29.52	4.57	3.83	2.73	
13	02-01-2024	Dal	Main Cour	Tuesday	0	0	29.27	125	27.67	23.47	22.5	5.91	4.95	3.91	
14	02-01-2024	Chapati	Main Cour	Tuesday	0	0	29.27	116	13.72	12.52	12.55	1.39	1.11	1.13	
15	02-01-2024	Pasta	Main Cour	Tuesday	0	0	29.27	120	29.44	31.11	29.44	0.05	0	0	
16	02-01-2024	Salad	Side	Tuesday	0	0	29.27	109	14.91	15.18	14.91	0.05	0	0	
17	02-01-2024	Dessert	Dessert	Tuesday	0	0	29.27	109	14.2	13.63	12.91	1.37	1.16	0.49	
18	03-01-2024	Biryani	Main Cour	Wednesda	0	0	25.38	110	51.06	44.1	43.98	8.31	6.79	6.55	
19	03-01-2024	Rice	Main Cour	Wednesda	0	0	25.38	103	29.02	27.18	25.99	3.37	2.83	1.67	
20	03-01-2024	Curry	Main Cour	Wednesda	0	0	25.38	107	34.56	29.99	29.91	5.47	4.32	4.3	

Fig. 3. Dataset snapshot.

The machine learning component is implemented using Scikit-learn and consists of Random Forest Regression and Gradient Boosting Regression models. The models are trained using the prepared historical dataset and evaluated using MAE, RMSE, and R^2. The evaluated models are compared to identify the production model used by the subsequent prediction and decision-support modules. The implemented Random Forest model achieved an MAE of 0.185 kg, RMSE of 0.343 kg, and R^2 of 0.988 on the evaluated test set, while Gradient Boosting achieved an MAE of 0.328 kg, RMSE of 0.459 kg, and R^2 of 0.978. Based on these evaluation results, Random Forest is used as the selected production model.

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The Food Waste Prediction module provides an interface through which operational information such as food item, category, customer count, expected demand, preparation quantity, consumption quantity, temperature, and event-related information can be provided. The input is passed through the same preprocessing and prediction pipeline used during model development. The selected regression model then produces the expected food-waste quantity in kilograms. The prediction result is displayed together with relevant operational information to make the output easier to interpret.

The What-If Analysis module extends the prediction functionality by evaluating alternative preparation quantities. The system generates multiple preparation scenarios around the baseline quantity and passes each scenario through the waste-prediction model. The resulting predicted waste and demand coverage are displayed together, allowing users to compare the consequences of different preparation decisions. This implementation provides the basis for the prescriptive component of the system.

The Preparation Recommendation module processes the scenario results and identifies a suitable preparation option according to the defined decision constraints.

The recommendation considers both predicted waste and demand coverage so that reducing preparation does not result in an unacceptable shortage. The selected scenario is presented to the user together with its predicted waste and expected demand coverage, thereby converting model predictions into actionable preparation guidance.

The Potential Surplus and Donation Analysis module uses the recommended preparation scenario and associated prediction results to estimate potential surplus food and potential donation quantity. The system presents these values as potential analytical estimates rather than guaranteed quantities available for redistribution. Food safety, quality, storage, and handling conditions must be considered before any actual donation or redistribution decision.

A web-based interface, named Food Waste Intelligence, integrates the implemented modules into a single application. The application contains separate interfaces for the historical dashboard, food-waste prediction, What-If analysis, surplus and donation analysis, analytics and model evaluation, and live end-to-end analysis. The dashboard presents historical food-waste information and model performance, while the Live Dashboard combines the complete workflow for new user inputs.

The backend provides the required prediction and analysis services through application programming interfaces. The machine learning model, scenario-analysis logic, recommendation engine, and surplus-analysis functions are connected through the backend so that the output of one stage becomes the input to the next stage. SQLite-based storage is used for application data and live analysis records, while the original historical dataset is preserved separately for model training and evaluation.

The implementation also provides a data-export facility for generating a combined analytical dataset. Historical records and saved live-analysis records can be exported while maintaining a distinction between historical observations and newly generated model predictions. This prevents predicted waste values from being incorrectly treated as actual observed waste during subsequent analysis.

The complete implementation therefore connects the predictive and prescriptive components into a unified workflow:

Historical Data → Preprocessing → ML Prediction → What-If Analysis → Preparation Recommendation → Potential Surplus → Potential Donation → Web-Based Decision Support

This implementation realizes the predictive-prescriptive framework proposed in the project and provides an interactive platform for food-waste analysis and preparation-related decision support.

VI. RESULTS

The proposed Food Waste Intelligence framework was evaluated using the prepared food-waste dataset containing 5,840 records covering 730 days and 8 food items. The dataset was divided into 80% training data and 20% testing data. Random Forest Regression and Gradient Boosting Regression were implemented and evaluated using Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and coefficient of determination (R^2).

A. Model Performance

The performance of the implemented regression models was evaluated on the test set using MAE, RMSE, and R^2. The evaluation was performed using an 80:20 train-test split with random_state = 42.

As shown in Fig. 4, Random Forest achieved an MAE of 0.185 kg, RMSE of 0.343 kg, and R^2 of 0.988, whereas Gradient Boosting achieved an MAE of 0.328 kg, RMSE of 0.459 kg, and R^2 of 0.978. Random Forest was therefore selected as the production model based on its lower prediction errors and higher R^2 value.

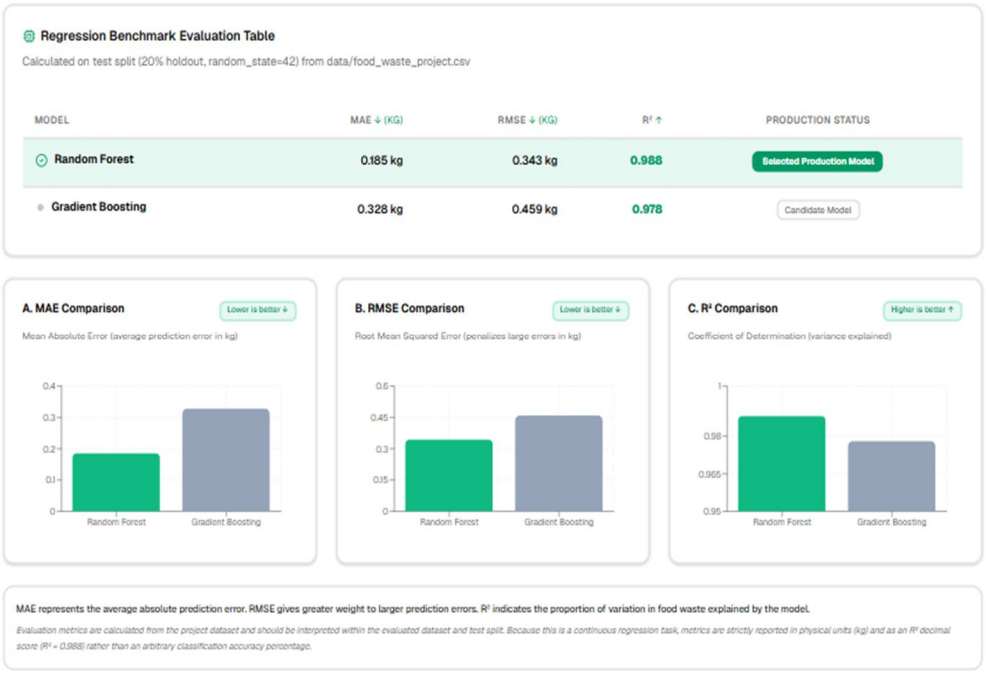


Fig. 4. Regression model performance comparison based on MAE, RMSE, and R^2.

B. What-If Scenario Analysis

The selected Random Forest model was integrated with the prescriptive analysis module to evaluate different food preparation quantities. The system generated preparation scenarios ranging from 80% to 120% of the reference preparation quantity.

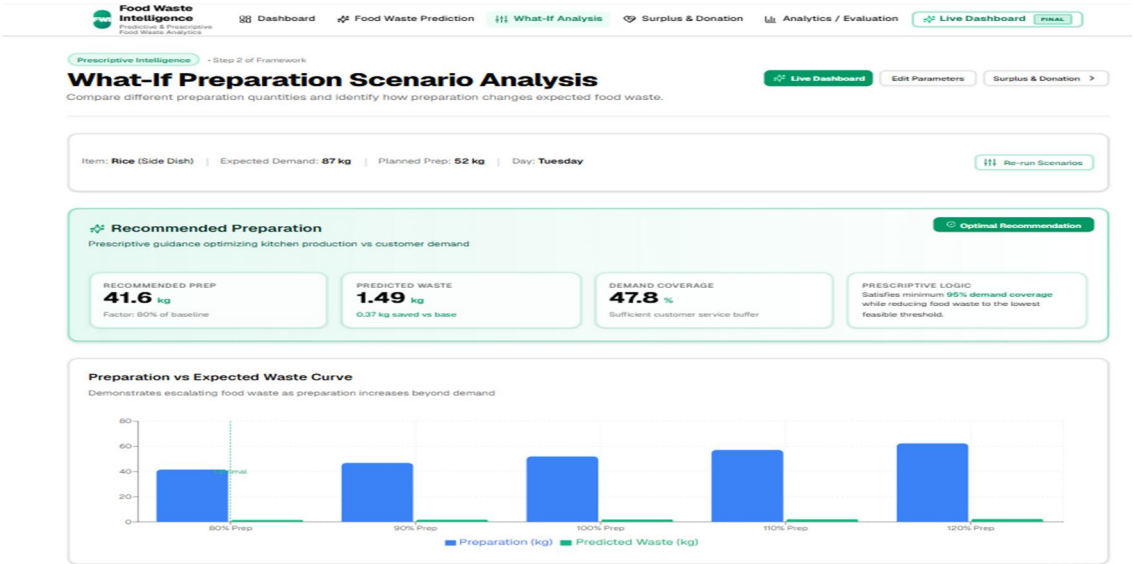


Fig. 5. What-If Preparation Scenario Analysis.

C. Surplus And Donation Analysis

The prescriptive analysis evaluated alternative preparation quantities and identified 41.6 kg as the recommended preparation quantity for the evaluated scenario. The corresponding predicted food waste was 1.49 kg, while the displayed demand coverage was 47.8%. The system estimated 0 kg of potential surplus and 0 kg of potential donation for this scenario. The results indicate that the evaluated preparation scenario did not generate recoverable surplus according to the implemented surplus calculation. Actual food donation would additionally depend on food-safety, quality, storage, and redistribution conditions.

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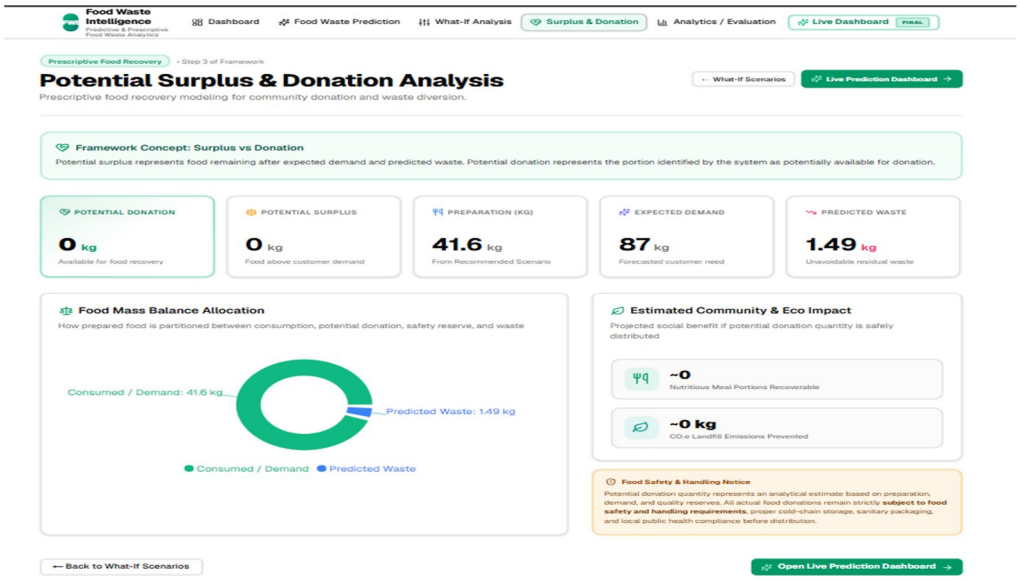


Fig. 6. Potential Surplus and Donation Analysis for the Evaluated Scenario.

D. Historical Dataset Analysis

The historical dataset contained 5,840 records across 730 days and 8 food items. The analysis provides an overview of food-waste patterns across food items and categories. The implemented analysis recorded approximately 19,031 kg of waste and approximately 15,522 kg of potential surplus across the dataset.

Among the analyzed food items, Biryani showed the highest average waste at approximately 5.75 kg/day, with approximately 4,200 kg of total waste in the dataset.

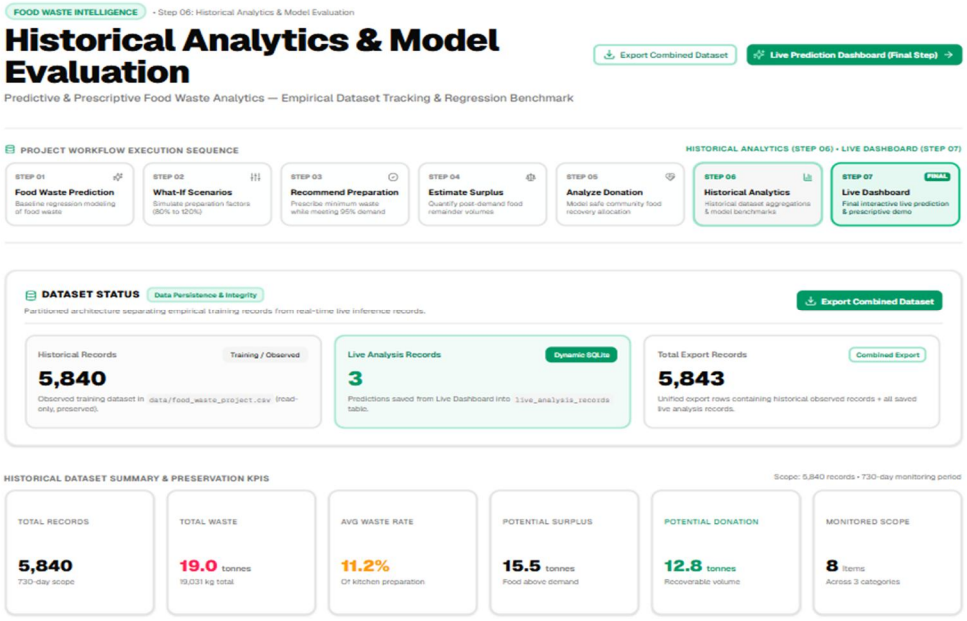


Fig. 7. Historical dataset summary and analytics evaluation.

E. Overall Result

The experimental results demonstrate that the proposed framework combines predictive and prescriptive analytics within a single workflow. The prediction component estimates expected food waste, while the what-if component evaluates alternative preparation quantities and the recommendation module identifies a feasible scenario based on demand coverage and predicted waste. The surplus and donation modules provide additional decision-support information.

VII. FUTURE SCOPE

The proposed Food Waste Intelligence framework can be further enhanced by incorporating real-time data collection through IoT-based sensors and automated weighing systems to continuously monitor food preparation, consumption, and waste. Future development can also include additional factors such as weather conditions, festivals, holidays, special events, and seasonal demand patterns to improve prediction capabilities. Integration with NGOs, food banks, and community organizations can support the effective utilization of potential surplus food, subject to food safety and quality requirements. The system can also be extended with mobile applications, multilingual interfaces, automated alerts, real-time monitoring, and advanced machine learning techniques. These enhancements can improve the scalability, accessibility, and practical applicability of the proposed framework.

VIII. CONCLUSION

Food Waste Intelligence: A Predictive-Prescriptive Machine Learning Framework for Food Waste Reduction and Surplus Donation Analysis successfully integrates machine learning-based prediction with prescriptive decision-making for food waste management. The system predicts expected food waste using historical food-service data and evaluates different preparation scenarios through What-If analysis. Based on these scenarios, the system provides a preparation recommendation while considering demand coverage and predicted waste. It further estimates potential surplus and potential donation opportunities and presents the results through an interactive web-based dashboard. The integration of prediction, scenario analysis, recommendation, surplus estimation, donation analysis, and analytics provides a unified decision-support framework for reducing avoidable food waste and improving the utilization of potential surplus food. The developed system provides a foundation for future real-time and scalable food waste management applications.

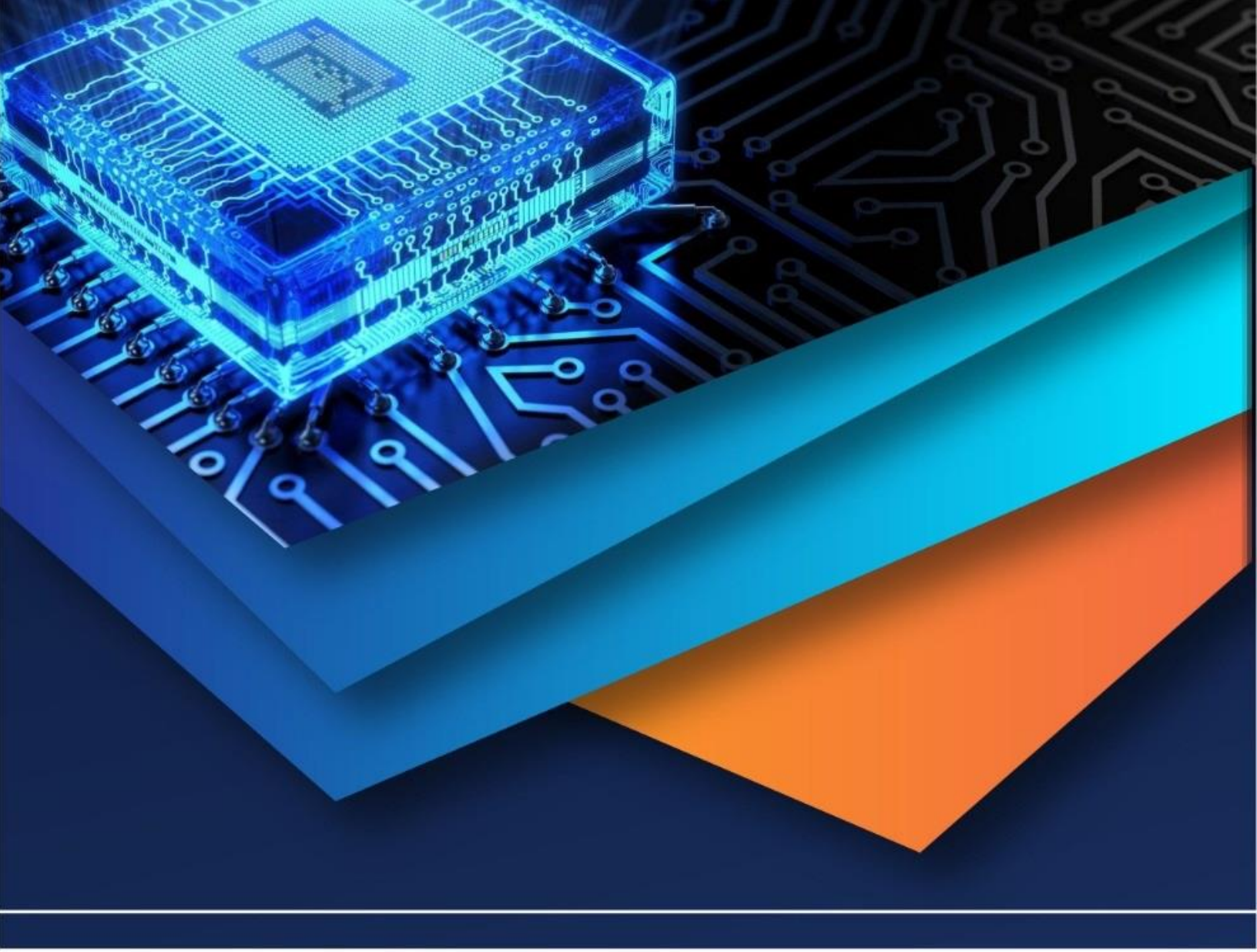
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