AI-Powered Personalized Allergen Detection and Recipe Modification Tool for Safer Meal Preparation

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ABSTRACT

The AI-Powered Personalized Allergen Detection and Recipe Modification Tool is a mobile application developed to assist individuals with food allergies helping them identifying harmful ingredients in recipes and offer safer alternatives tailored to their personal allergen profiles. Food allergy is a serious health concern that can lead to life-threatening reactions if not managed properly, especially when consuming meals with unfamiliar ingredients. This tool uses artificial intelligence (AI) and natural language processing (NLP) to analyse the textual format recipes specified by users and intelligently detect the presence of any allergen substances. Once allergens are identified, the tool accesses a built-in database integrated with machine learning/large language model to suggest appropriate and non-allergenic substitutes, allowing the users to prepare and modified a safer recipe. The tool includes features such as creating, editing, sharing, favouriting, and deleting recipes, along with user account settings that support allergen input and password management. With a focus on 90% accuracy rate in allergen detection and 44% substituion relecance score, the app ensures both speed and reliability. The tool was developed specifically for Android platform and intended for online use has provide an intuitive and user-friendly interface designed for convenience and efficiency. The tool helps users to make informed decisions about the ingredients and substitutions and early user feedback indicates improved confidence in meal preparation.

Keywords: Food Allergy, Allergen Detection, Recipe Modification, Artificial Intelligence (AI), Mobile Health Application

INTRODUCTION

Food allergies are a growing global public-health concern, affecting both children and adults. They occur when the immune system misidentifies certain food proteins as harmful, causing symptoms that can range from mild irritation to life-threatening anaphylaxis [1]. The U.S. Food and Drug Administration estimates that millions of people worldwide experience food-related allergic reactions annually, and that strict avoidance of the offending foods remains the only reliable preventive measure [1]. In the United States alone, approximately 6 percent of adults and 8 percent of children live with at least one diagnosed food allergy. The “Big 9” allergens: milk, eggs, peanuts, tree nuts, wheat, soy, fish, shellfish, and sesame are responsible for most severe reactions [2].

Despite labelling regulations and increased public awareness, individuals with food allergies continue to face difficulties when preparing or consuming meals. Hidden allergens in complex or processed foods are especially problematic, and manual ingredient checking is both time-consuming and error prone [3]. Traditional recipe or nutrition applications typically provide static ingredient databases and do not support real-time allergen detection or personalized substitution recommendations. These shortcomings restrict dietary variety and elevate the risk of accidental exposure.

Recent studies have shown artificial intelligence (AI) and natural language processing (NLP) are able to analyze

ingredient list, detecting allergen presence and suggest safe substitution automatically for intelligent dietary management system [4]. Studies have demonstrated AI's potential to improve allergen detection accuracy, enhance dietary planning, and support patient decision-making in real-time environments [5]. However, few mobile applications integrate these intelligent capabilities with user-centred interfaces that allow recipe creation, allergen analysis, and ingredient modification within a single tool.

This study develop the tool using React Native and MySQL backend that uses AI -based API to identify allergens and suggest safer substations. The tool enables users to input and edit recipes, analyses ingredients using NLP for allergen detection, and proposes appropriate, safe substitutions. The integration between AI technology and mobile accessibility shall empower individuals with food allergies in preparing safer meals, promotes a healthier and more inclusive dietary practices [4], [6].

Background

Food allergies are increasingly recognized as a major global health issue with a rising prevalence across all age groups. Recent studies highlight that the incidence of both adult and infant food allergies has continued to grow worldwide, primarily due to changes in diet, food processing, and environmental factors [7]. Despite ongoing efforts to improve labelling and awareness, accidental allergen exposure remains common in daily food preparation and consumption. Conventional recipe databases and nutrition-tracking applications focus largely on nutrient values rather than allergen safety, leaving users to manually identify allergens, a process prone to error and inefficiency.

Advancements in artificial intelligence (AI) and machine learning (ML) have provided promising tools for improving food-safety monitoring and allergen detection. AI algorithms can analyse ingredient-level data, identify hidden allergenic proteins, and predict potential reactions using pattern-recognition models. Recent work by Yang et al. [8] demonstrated a novel AI-driven method using near-infrared spectroscopy (NIRs) for early detection of non-specific lipid transfer protein (nsLTP) allergens, enabling fast and non-destructive screening. Similarly, Li et al. [9] developed a portable fluorescence biosensing system enhanced with AI, capable of detecting multiple allergens simultaneously, marking a significant leap toward real-time, point-of-care allergen identification.

Beyond detection, the integration of AI into personalized nutrition has fostered the rise of precision nutrition an approach that tailors dietary recommendations to an individual's genetic, physiological, and lifestyle factors. Deep learning models that combine microbiome and diet data have demonstrated effectiveness in predicting optimal nutrition strategies and allergy risk profiles [10]. These developments lay a strong foundation for intelligent applications that not only identify allergens but also assist users in modifying recipes according to their unique health needs.

The adoption of mobile health (mHealth) technology further enhances accessibility and real-time feedback in dietary management. Smartphones serve as effective platforms for hosting AI-powered food-safety applications, allowing users to receive instant allergen detection and substitution suggestions. However, most existing mobile apps are limited to static allergen lists and lack adaptive learning capabilities [11]. Thus, integrating AI and NLP in mobile health technologies allowed our tool to provide personalized allergen detection that improves the user's confidence in their food choices [8], [9].

Related Work

Recent developments in artificial intelligence (AI) and machine learning (ML) have revolutionized food safety, quality assurance, and health-related analytics. The adoption of AI-driven systems enables automated data processing and real-time decision-making, particularly in detecting contaminants, allergens, and nutritional irregularities. Revelou et al. [12] provided a comprehensive review of AI and ML applications in food safety and quality control, emphasizing their success in industrial environments for contamination detection and inspection automation. However, their work focused primarily on large-scale production systems and lacked attention to personalized allergen management.

A growing body of research now explores AI's role in allergen detection and classification. Sarlakifar et al. [13] introduced AllerTrans, a deep learning (DL) framework designed to predict protein allergenicity using sequence-level features. The model demonstrated improved precision and recall rates for allergen prediction compared with conventional classifiers. Similarly, Liu et al. [14] proposed a computational model integrating multiple feature types, such as sequence patterns, physicochemical properties, and evolutionary profiles to improve allergenic protein prediction accuracy. Despite these advances, both studies were confined to laboratory-based datasets and did not address real-world dietary applications or mobile implementation for consumers.

Kim et al. [15] extended the application of AI to food safety and contamination control by incorporating computer vision and ML algorithms into automated quality inspection systems. Their findings reinforced AI's reliability in ensuring food integrity throughout the supply chain. Yet, this research remains limited to industrial settings and lacks a personalized dietary component.

Meanwhile, Chen et al. [10] explored the concept of precision nutrition through deep learning techniques applied to microbiome and dietary data. Their study demonstrated that AI can deliver tailored nutrition recommendations to improve health outcomes, but the framework did not consider allergen avoidance or recipe adaptation for allergic individuals.

Collectively, these works affirm the growing importance of AI in food safety and health personalization. However, most of the reviewed studies focus either on industrial quality control or theoretical allergen modelling rather than user-centric applications. There remains a substantial gap in research concerning the integration of AI-based allergen detection, NLP-driven recipe analysis, and mobile accessibility within a single, interactive platform.

Table1 Summary of Related Works

Ref	**Method / Approach**	**Key Findings**	**Identified Research Gap**
[12]	Review of ML and AI methods applied to food inspection and contamination detection	Provided an overview of how AI improves food-quality assurance and safety monitoring in industrial contexts	Focused on industrial food inspection; no personalization or allergen-specific application
[13]	Deep learning model (AllerTrans) for protein allergen classification	Developed a DL framework with higher accuracy for predicting allergenic proteins	Limited to laboratory datasets; lacks real-world, user-level integration or mobile deployment
[14]	Multi-feature fusion (sequence, physicochemical, and evolutionary features)	Achieved improved allergen prediction through multi-feature data fusion	Computational focus; no recipe-level or dietary personalization component
[15]	AI-driven visual and chemical food-quality inspection	Demonstrated AI's role in automating contamination control and quality assessment	Industrial and product-level orientation; does not support personalized food-safety management
[10]	Deep learning on microbiome and dietary data	Established AI frameworks for individualized diet optimization and health improvement	Focused on nutrition personalization; no allergen detection or recipe modification functionality

METHODOLOGY

The Allergen Detection and Recipe Modification Tool was developed using a systematic agile software development process. The process consist of four major phases which are analysis, design, implementation and testing. The implementation and testing were executed iteratively ensuring the functional and non-functional requirements effectively translated into mobile solution that is designed to identify allergens, recommend substitution and enhancing user safety in meal preparation.

Analysis Phase

The analysis phase is aimed to understand the overall behaviour of the tool. The Allergen Detection and Recipe Modification Tool requirements are modelled using the use case diagram presented in Fig 1. The main actor of application is the User, who interacts with the system to perform several key actions. These include registering an account, customizing recipes, tracking recipe trials, and sharing customized recipes with others. These core functions represent the primary ways users engage with the application to manage their food allergies and personalize their cooking experience.

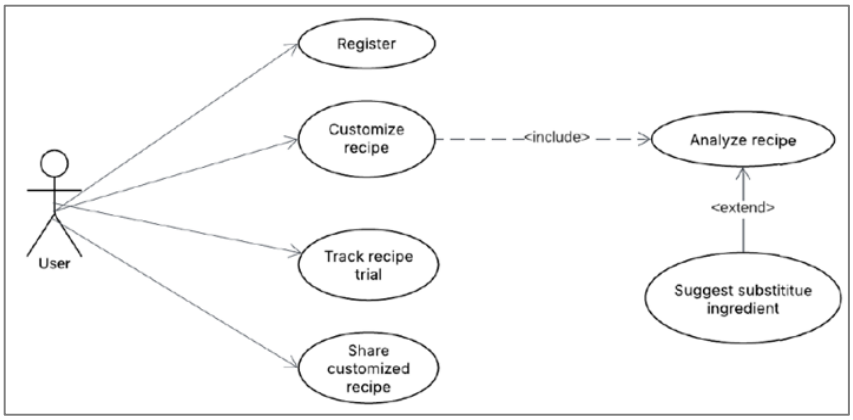

Fig1. Use case diagram proposed application

A central use case in the diagram is Analyze Recipe, which captures the system's ability to examine the ingredients of a recipe provided by the user. This analysis is essential for identifying potential allergens based on the user's personalized allergy profile. Extending from this use case is Suggest Substitute Ingredient, which is triggered when allergens are detected. This optional feature provides safe and suitable ingredient alternatives, allowing users to modify their recipes effectively. The diagram emphasizes the tool's user-centric design, focusing on practical features that support safe and informed meal preparation while promoting ease of use and personalization.

Design Phase

The design phase focused on transforming the tool requirement that was previously defined in the analysis stage into an architectural framework that support efficient data processing, scalability, and user accessibility. The architectural framework consist of several modules as illustrated Fig 2.

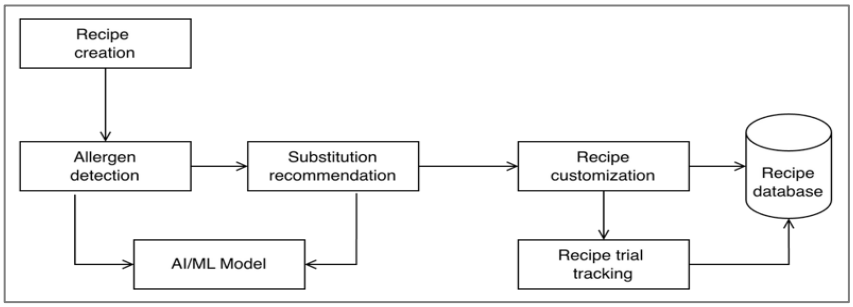

Fig 2.The Allergen Detection and Recipe Modification Tool architectural workflow

The framework begins with Recipe Creation module. This module interfacing with the user to accept the recipe. The user will send the recipe for allergen analysis through an API Gateway. This gateway acts as a centralized entry point, efficiently directing traffic to the appropriate backend services.

The Allergen Detection module responsible to analyse the user recipe. The module is the most critical component in the architecture where ingredients are identified, extracted and analysed using an AI/ML model. The AI/ML model is an encapsulated large language model (LLM) library consist of intelligent algorithms trained various text documents. The AI/ML model determined the allergen presence in the recipe based on the user dietary and allergen profile. The identified ingredients are compiled to be processed in the next module.

The Substitution Recommendation module uses the AI/ML model to provide safe ingredient options based on the identified user allergenic ingredients for the user. The options were gathered and presented to the user. The tool is designed to allow user to select the recommended ingredients instead of deciding for the user.

The Recipe Customization module allow the user to substitute the allergenic ingredients with the recommended ingredients. The module manage the customized recipe and saves it the database for the user future's reference and use.

The Recipe Trial Tracking module records the number of user attempt and feedback. The feedback serves as a continuous allergy monitoring loop for the user enhancing meal preparation safety.

Development Phase

The implementation phase marks the transition from design to a functional tool for the Personalized Allergen Detection and Recipe Modification Tool. This phase focused on translating the architecture framework, data design, and user interface design into an operational mobile application. The development began with setting up the software environment using React Native for cross-platform front-end development and MySQL as the backend database. Tools such as Android Studio, Visual Studio Code, and MySQL Workbench were configured to streamline development, testing, and debugging processes. The API layer which is hosted at http://67.205.160.200:5000, acted as the bridge between the mobile app front-end and backend and managing communication for all modules described in Fig 2.

Each module was implemented in iteration, adhering to the Agile principle. The iteration modularised the development artefacts that results in ease of testing, debugging and maintenance. The Account Registration and Authentication modules were first to be developed. These modules allowed users to securely create and access accounts using encrypted credentials. Once these modules were established, the Recipe Creation modules were built to handle recipe creation, editing, deletion, and sharing. Next, the Allergen Detection module was developed and integrated into the development. Then followed by Substitution Recommendation module. In these two module, access to AI/ML module was embedded, realizing the safer approach in meal preparation. The Recipe Customization module were added after that, realizing the personalization aspect of the tool. Finally, the Recipe Trial Tracking module were integrated into the tool to rate recipes, indicate preparation difficulty, and report whether substitutions were effective or safe, enhancing personalization and tool learning.

Version control was maintained throughout development using a systematic commit and review process, ensuring stable integration of new features and allowing rollback when necessary. The frontend application communicated through an API gateway to the backend services, including user management, recipe management, and allergen detection services. These components interacted with the user and recipe databases to store and retrieve data efficiently.

Testing Phase

The testing phase aimed to validate the functionality, performance, and usability of the Allergen Detection and Recipe Modification Tool, ensuring it met user requirements and project specifications. A structured testing process was followed, combining functional, integration, and user acceptance testing (UAT). This systematic approach allowed for early defect identification, iterative correction, and the delivery of a stable and user-friendly application.

The testing were focusing on two critical modules which are the Allergen Detection and Substitution Recommendation. The test cases for these modules are describe in Table II. The testing was conducted in a controlled environment comprising the developer's workstation and user mobile devices. The tool APK was installed on Android devices running version 8.0 and above, with evaluations conducted under both Wi-Fi and 4G/5G mobile networks to simulate real-world conditions. Tools such as Android Studio, MySQL Workbench, and Microsoft Survey were employed for functional validation, data management, and feedback collection. Manual test documentation and bug-tracking logs were used to record results and ensure traceability across all testing cycles.

Table 2. Test Cases

Test Case	**Scenario**	**Input Condition**	**Expected Output**
TC01	Basic Allergen Detection	Recipe: Peanut Butter Sandwich	Peanut is detected and highlighted.
TC02	Multi-Allergen Detection	Recipe: Creamy Pasta with Peanut Sauce (contains milk & peanuts)	Peanut and milk are detected highlighted.
TC03	Hidden Allergen in Compound Ingredient	Recipe: Soy Sauce Chicken	Soy is detected.
TC04	Nested Ingredient Parsing	Recipe: Pad Thai (contains fish sauce, peanuts)	Fish sauce and peanut are detected.
TC05	Substitution Recommendation – Simple	Recipe with peanuts	Sunflower seeds or pumpkin seeds are recommended.
TC06	Substitution Recommendation – Multi-Allergen	Recipe with milk & peanuts	Oat milk and, sunflower seeds are recommended.
TC07	Culinary Intent Preservation	Recipe: Thai Peanut Sauce	Almond butter or tahini is recommended to maintain texture
TC08	Regional Ingredient Parsing	Recipe: Roti Canai with Ghee	Ghee is detected from milk allergen
TC09	Complex Recipe Parsing	Recipe: Vegetarian Sushi (contains soy sauce, mayonnaise)	Soy and egg allergens detected
TC10	Adaptive Substitution for Complex Dish	Recipe: Seafood Paella (contains shellfish, fish stock)	Plant-based seafood alternatives and vegetable broth are recommended.

The test results demonstrated that all test cases described in Table II are compiled and recorded in Table III. The Allergen Detection module performed at 90% accuracy for correctly detecting allergen in the recipe. The module perform at 92% success rate for correctly handling multiple allergen in a recipe. The high success rates shows the module robustness handling single and multiple allergen detection in a recipe. Apart from explicit allergens presence, the module was tested to complex ingredient. The module performed at 85% accuracy on complex ingredient, showing a competitive advantage to the module.

The relevance score metrics is used to measure the contextual appropriateness and correction for the Substitution Recommendation module. The module achieved 47% score, indicating the tool struggle to maintain the original recipe intent with the substituted ingredient.

Table3. Testing Results

Metrics	Description	Result
Accuracy	Correct allergen detection	90%
Multi allergen success rate	Correct handling of multiple allergens	92%
Complex Ingredient Parsing Accuracy	Correct detection in compound ingredients	85%
Substitution Relevance Score	Culinary intent preserved in suggestions	44%

Other modules which are Recipe Creation, Recipe Customization and Recipe Trial Tracking are tested during User Acceptance Test (UAT). The UAT results shows the app is perceived as highly effective in accidental allergen exposure prevention with 70 Net Promoter Score (NPS), as illustrated in Fig 3. The UAT involves 30 respondents, where 21 promoters were recorded, indicating strong satisfaction on the tool and the likelihood to recommend or influence other to user the tool is high. While 9 respondents were recorded as passives, indicating moderately satisfy with the tool even though the likelihood to recommend or influence other to use the tool is low. Importantly, there were no detractors**,** which reflects a positive overall user experience. The high NPS score demonstrating a strong trust in the app capability analysing, identifying allergen presence and substitution recommendation in different degree of recipe complexity. Furthermore, the absence of major defects during UAT, confirming the tool's stability and reliability for deployment.

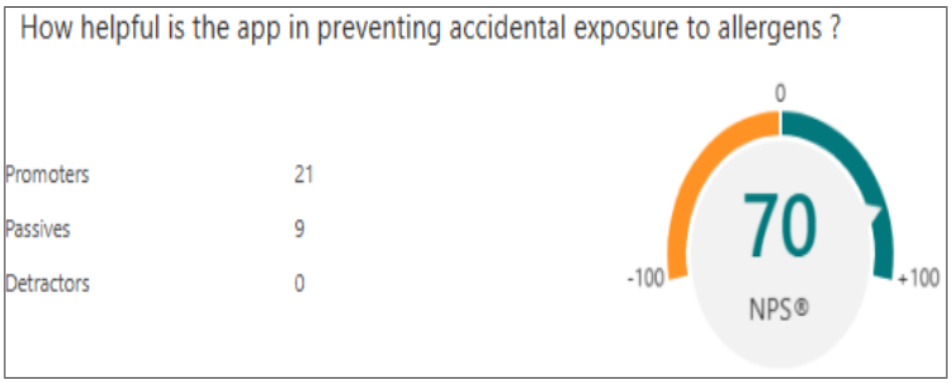

Fig3. Net promoter score of proposed application

In summary, the testing phase validated that the developed tool achieved its objectives of accurate allergen detection, intuitive recipe modification, and high usability. The combined results from functional and user acceptance testing confirm that the AI-Powered Personalized Allergen Detection and Recipe Modification Tool is ready for real-world use, offering a reliable and effective solution for food allergy management and safe recipe customization.

RESULT

The results presents the outcomes of the tool implementation, highlighting the actual user interfaces and functionalities of the Allergen Detection and Recipe Modification Tool. The developed tool is a mobile app that integrates user authentication, allergen detection, ingredient substitution, and feedback management within a single responsive interface. The screenshots captured during testing and deployment to visually demonstrate the proper functioning of each module according to its intended purpose.

User Authentication and Onboarding Modules

A new user will be guided through a secure onboarding process. The Sign-Up Screen in Fig 4 allows the user to create an account by providing essential details including as full name, email address, and password. Upon a success onboarding process, the registered user can access the tool using the Log In Screen as shown in Fig 5.

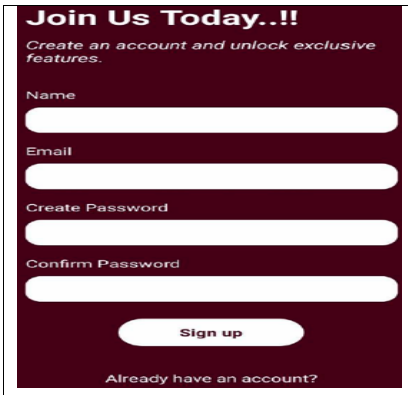

Fig. 1. Registration screen

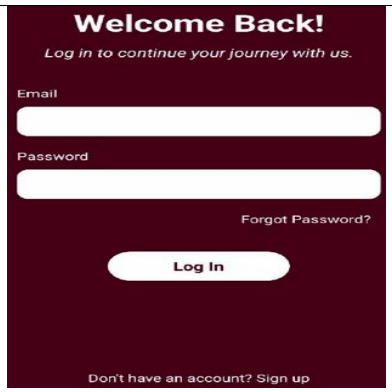

Fig. 2. Login screen

The user may recover a forgotten password using the screen shown in Fig 6. Subsequently, a one-time password will be emailed to the user to be provided in the screen in Fig 7. The OTP facilitate a secure password reset workflow ensuring user data remains protected.

Fig. 3. Forget password screen

Fig. 4. OTP verification screen

Core Application Dashboard

Upon success authentication, users are directed to the Home Screen, shown in Fig 8. The Home screen used an intuitive navigation design which featuring a search bar, a personalized welcome message, quick-access modules to "Favourites," user-created recipes, and community feedback. A bottom navigation bar ensures seamless movement between the application's primary sections.

Fig. 5. Home screen

Fig. 6. Create recipes screen

Recipe Creation

The central functionality of the tool is the recipe creation. The tool provides two approaches to create a recipe. The first approach is using a standard form as shown in Fig 9. In the form, the user is required to specify the recipe title, description, supporting image and a list of ingredient.

Allergen Detection and Substitution Recommendation

The tool analyse the recipe and identify the allergen presence in the ingredient. Subsequently, the tool proactively display the Substitute Ingredients screen shown in Fig 10 after it detects allergenic ingredient that best march the user's allergen profile. The screen suggest safe alternative ingredient to substitute with the allergenic ingredients. The tool allow the user to customize the recipe using the listed substitute ingredient.

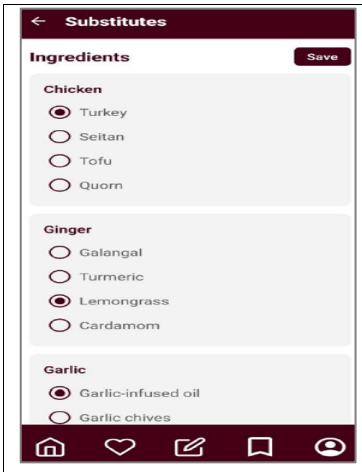

Fig. 5. Substitute ingredients

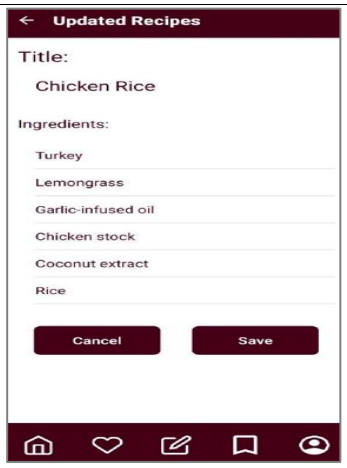

Fig. 6. Updated recipe screen

The tool display the customized recipe as shown in Fig 11. It is essential for the tool to confirmed with the user on the customized recipe before automatically saved it into the recipe repository. The confirmation adds another safety layer in food allergy management and meal preparation.

Recipe Management and Sharing

The tool offers comprehensive feature for managing personalized recipes. All saved recipes are accessible from the Saved Recipe Screen shown in Fig 12, which includes a search function. Selecting a recipe will provides a detailed view, clearly distinguishing between original and substituted ingredients, and offers options to favourite, share, or delete. The Share Recipe Screen (Figure 9) allows users to easily distribute their safe, customized recipes through other platforms like WhatsApp and email.

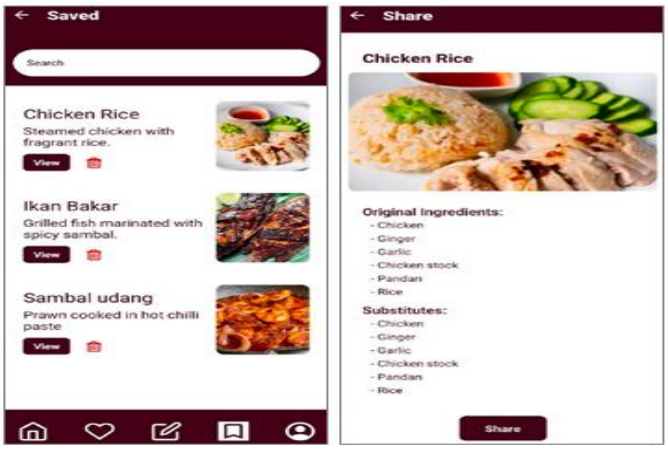

Fig. 7. Save and share recipes screen

User Feedback and Profile Customization

User feedback to track the effectiveness of the substituted ingredients used in the customized recipe is a critical feature. The tool provide a mean of tracking the user attempt or trial on the customized recipe as shown in Fig 13.

The user maintain their account information using the screen in Fig 14. In some cases, the user might develop a new food allergy or may no longer allergic to certain kind of food. The tool include the food allergy dynamics that allows the user to update the allergenic food profile using the screen in Fig 15. The screen is accessible from Fig 14. The screen in Fig 15 shall maintain the most up to date allergenic food information. Apart from ensuring a safe meal preparation, the tool shall ensure the user essential nutrient according the user's current allergy condition.

Additional tool safety measure is provided which allowing the user to update the password from time to time using the screen shown in Fig 16.

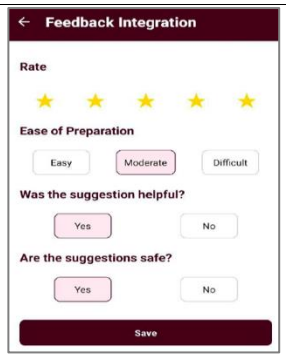

Fig. 8. Feedback integration screen

Fig. 9. Account update screen

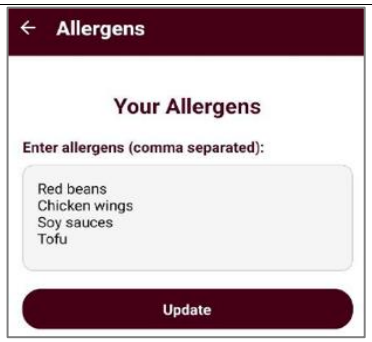

Fig. 10. Allergens update screen

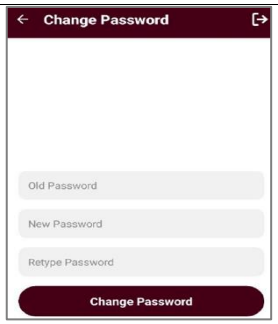

Fig. 11. Change password screen

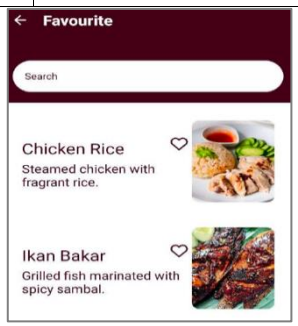

Fig. 12. Favorite recipes screen

Favoriting a recipe is another safety measure in meal preparation and food allergy management. The favorite-marked recipe is an allerged-checked and safe recipe that shall minimize accidental exposure to risky ingredient.

Besides that, a favorite-marked recipe provide quick access to the recipe leads to efficient time planning in preparing the meal. Furthermore, it this feature encourage better user engagement with the tool.

CONCLUSION

The development of the Allergen Detection and Recipe Modification Tool successfully achieved its primary goal of creating an intelligent mobile app solution that assists users in identifying potential allergens in food ingredients and suggesting safe alternatives. The tool integrates mobile app technology, structured user allergen profile, AI and NLP model to analyse the user recipes. The integration has consistently identified allergens and recommend substitute ingredients with high reliability during testing. The completed tool aligns with the objectives established during the analysis and design stages, proving to be both technically feasible and functionally effective.

Throughout the project, each development phase—from analysis to testing was systematically executed. The analysis phase defined clear user requirements, focusing on allergen safety and dietary personalization. The design and implementation phases translated these requirements into a robust architectural workflow, ensuring modularity and scalability. The testing phase validated all core functionalities through black-box and functional testing, where all test cases achieved successful results. The results phase, supported by actual tool screenshots, confirmed that each module: registration, login, allergen detection, substitution, feedback, and recipe creation operated according to specification, demonstrating the tool's readiness for real-world deployment.

The tool contributes to the broader field of health-aware food technology, emphasizing preventive allergen management through mobile app solution. Its success lies not only in accurate allergen identification but also in promoting safe recipe adaptation, helping users maintain their preferred diets while avoiding allergenic risks. The application's design ensures accessibility for users with varying technical literacy and provides a framework that can be enhanced for larger databases or regional food variations.

In conclusion, the Allergen Detection and Recipe Modification Tool has proven to be a reliable, efficient, and user-friendly platform that supports personalized allergen management. The combination of intelligent detection, substitution logic, and real-time interaction demonstrates how modern technology can improve food safety and quality of life for individuals with food allergies. This project establishes a solid foundation for future research and development in mobile health applications that integrate AI-driven decision-support tools for dietary management.

Future Works

For future development, we plan to improve the tool accuracy and privacy feature while exploring clinical collaboration feature to increase its practical use. First, adding robust image-based food recognition feature would greatly reduce the manual entry effort and improve usability. In the recent reviews and empirical work, the deep learning models has demonstrated its capability to achieve high accuracy for food item recognition and volume estimation [16]. Besides that, the models enables automatic ingredient extraction from photos for subsequent allergen analysis [16], [17].

Second, integrating large language models (LLMs) or fine-tuned transformer models for ingredient understanding and substitution can improve the quality and contextual relevance of replacement suggestions; recent experiments demonstrate LLMs' ability to propose nutritionally informed and phytochemical-aware ingredient substitutions that preserve culinary intent while meeting dietary constraints [18]. The user privacy can be enhanced in the future updates by integrating federated learning in the tool. This integration will enable the tool to learn from user interaction without collecting personal data explicitly [19].

A feedback loop process integrated with reinforcement learning technique should be established in the future to improve user engagement with tool. Besides that the data collected from the previous screen should be use to analyse the user preference and dynamics of food allergy to improve a safer recommendation. Furthermore, the access to variety of recipes in the database shall provide allergen-approved and safe options to the user.

Furthermore, expanding multilingual label and ingredient parsing is essential for global deployment: building or adopting multilingual OCR and NLP pipelines (and curated multilingual ingredient datasets) will reduce false negatives caused by non-English labels and localized ingredient names, improving detection across cuisines and regions [16], [17].

Finally, coupling the application with user-centric personalization, such as adaptive recommendation engines that learn from individual feedback, clinical severity, and (optionally) microbiome or wearable data can make substitution suggestions and alerts more clinically relevant and acceptable to users, while careful user consent flows and transparent explanations (explainable AI) will help maintain trust and safety. Together, these enhancements would move the app from a rule-based detector to an intelligent, privacy-aware, and globally usable decision-support tool for allergy-safe eating.

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