Optimization of Honey Powder Formulation, Chemical Quality, and Antioxidant Activity Using Adaptive Feature Selection Based Multitarget Learning Approach

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Abstract. This study focused on predictive system using adaptive feature selection multitarget learning (AFS-MTL) to optimize powdered honey formulation through the selection of the most influential variables, including honey content, filler type and ratio, drying method, temperature, time, and supporting additives. The research employs three machine learning random forest, support vector machine (SVM), and XGBoost to predict optimal formulations and identify key features influencing powdered honey quality. The analysis focused on chemical parameters (moisture content, water activity, Hydroxymethylfurfural (HMF), reducing sugars, diastase enzymes, and antioxidant activity: 1,1-Diphenyl-2-Picrylhydrazyl (DPPH), 2,2-Azinobis-3-Ethylbenzothiazoline-6-Sulphonic Acid (ABTS), total phenols, and total flavonoids). Acacia monoflora honey was pretreated by evaporation and pasteurization to reach 20% moisture, maltodextrin and gum arabic were used as fillers, and anti-caking agents were used as materials. Results from stage I analysis demonstrated that the AFS-MTL framework effectively filters suboptimal formulations while improving prediction efficiency and accuracy compared to conventional trial and error methods. This approach has high potential for improving predictive accuracy, formulation efficiency, and product standardization in powdered honey production.
Keywords: honey, formulation, fillers, powder, machine learning.

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1 Introduction

Honey is a natural product produced by bees through nectar transformation involving enzymatic, evaporative, and biochemical processes. Indonesia, with its vast tropical forests and favour able climatic conditions, has high potential for honey production [1]. However, raw honey is often unstable due to its high moisture content, which promotes fermentation and quality degradation during storage. Converting liquid honey into a powdered form offers several advantages, such as improved shelf life, reduced hygroscopicity, and easier handling and transportation [2]. The drying process generally employs spray drying or vacuum drying, with fillers such as maltodextrin (MD) and gum arabic (GA) used to prevent stickiness and enhance product stability. The optimal formulation, however, is influenced by multiple interacting parameters, such as the drying temperature, honey-to-filler ratio, and drying time, making manual optimization via trial-and-error methods inefficient, costly, and time-consuming. Recent advances in artificial intelligence (AI) and machine learning (ML) offer innovative approaches for optimizing complex food formulations. Adaptive feature selection multitarget learning (AFS-MTL) enables simultaneous prediction of multiple target variables while selecting the most relevant features, thus improving predictive accuracy and interpretability [3]. Algorithms such as random forest, SVM, and XGBoost have proven effective in handling nonlinear, multivariate data in food system modelling [4]. This research integrates machine learning and food technology to construct a predictive system capable of identifying optimal formulation parameters for honey powder production on the basis of both chemical quality and antioxidant performance.

2 Materials and methods

2.1 Materials

The main ingredient used was Akasia monofloral honey (*Apis mellifera*), which was pretreated by evaporation and pasteurization to achieve 20% moisture. Two fillers, maltodextrin (MD) and gum arabic (GA), were used with the anti-caking agent SiO_2. The experimental treatments consisted of two drying methods (spray drying and vacuum drying), two fillers (MD and GA), and two honey to filler ratios (1:2 and 1:1,5), resulting in eight treatment combinations, each processed in 200 g batches. The research equipment consisted of a high-specification computer. Dataset (machine learning) Adaptive Feature Selection Multi-Target Learning (AFS-MTL) with 3 types of algorithms: random forest, support vector, and XGBoost. Chemical analyses employed standard laboratory equipment such as ovens, desiccators, high-performance liquid chromatography (HPLC) (for sugar composition), UV-Vis spectrophotometers (for antioxidant assays), and drying apparatuses (Buchi B-290 spray dryer and vacuum oven). Excel spreadsheets were used for processing the initial formulation data. Thedataset from the experimental phase was used as training and testing data for machine learning (ML) modelling.

2.2 Methods

The study employed a machine learning life cycle approach to identify the optimal powdered honey formulation. Data processing was conducted through sequential stages, including objective definition, data preparation, model construction, and performance evaluation. Random Forest, Support Vector Machine, and XGBoost algorithms were utilized in the modelling process. Adaptive feature selection–based multitarget learning was implemented as a quality screening mechanism, ensuring that only formulations satisfying predefined quality standards were selected. The analytical outcomes were subsequently used to generate recommendations for the most optimal powdered honey formulation.

2.3 Preparation of drying honey powder

The preparation for drying honey powder involves preconditioning the honey mixture by adjusting its viscosity and solid concentration to ensure uniform drying performance. For both vacuum drying and spray drying, the mixture is first homogenized with selected fillers such as maltodextrin or gum arab until a consistent slurry is formed. In spray drying, the feed is typically processed at inlet temperatures ranging from 150–170°C and outlet temperatures ranging from 80–90°C, allowing rapid water removal while minimizing thermal degradation. In powdered honey, one of the main disadvantages of drying via spray drying is the large amount of filler (35–50%) added to avoid stickiness [5]. Under vacuum drying, the process operates at much lower temperatures, generally 50–70°C, with reduced pressure conditions that facilitate moisture evaporation without excessive heat exposure. These temperature ranges are selected to balance drying efficiency and product quality, maintaining the natural antioxidant and enzymatic properties of honey.

2.4 Formulation of honey powder mixtures

The formulation of honey powder was prepared by blending acacia honey with fillers such as maltodextrin (MD) and gum arabic (GA) at ratios of 1:2 and 1:1,5, followed by the addition of silicon dioxide (SiO_2) as an anti-caking agent. Maltodextrin acts as an effective carrier and stabilizer because of its high solubility, neutral taste, and ability to reduce stickiness and hygroscopicity during the drying process [6]. Gum arabic, on the other hand, provides excellent emulsification and oxidative protection, although it tends to produce powder with slightly higher hygroscopicity [7]. The combination of MD and GA improves powder stability, flowability, and retention of bioactive compounds such as phenolics and flavonoids [8]. SiO_2 addition enhances powder flow and prevents agglomeration, improving storage stability [9]. The formulation was further optimized via the adaptive feature selection multitarget learning (AFS-MTL) approach to predict the best feature combinations among honey content, filler type, and drying method, resulting in honey powder with high solubility, stability, and antioxidant activity suitable for functional food applications [10].

2.5 Parameter measurement

Powdered honey parameters were evaluated to determine the best chemical quality and antioxidant activity produced from the optimal formulation. Moisture content testing revealed an ideal value of 3–5%, indicating the efficiency of the drying process and product stability. The optimal water activity (Aw) value was recorded in the range of 0.30–0.40, which ensures high shelf life and prevents the growth of microorganisms. The reducing sugars reached the best value of 65–75% w/w, in accordance with SNI standards, indicating a perfect sucrose inversion process. The optimal diastase enzyme activity was ≥8 Gothe units, reflecting enzymatic stability without significant thermal degradation. The sugar composition with a fructose:glucose (F/G) ratio of 1.2–1.4 shows high stability against crystallization.

In terms of antioxidant parameters, the best results are shown by an IC_{50} DPPH value of <50 ppm and an IC_{50} ABTS value of 50–100 ppm, which indicates very strong to strong antioxidant activity. The optimum total phenol content (TPC) reached 150–250 mg GAE/g, whereas the total flavonoid content (TFC) ranged from 50–100 mg QE/g, both of which reflect high bioactive content that was stable during drying. Overall, the combination of low moisture content, controlled water activity, and high antioxidant activity indicates that the best powdered honey formulation was obtained at a honey:filler ratio of 2:1 via maltodextrin with the spray drying method at a temperature of 150–160°C.

2.6 Data Analysis

The dataset was analysed using three machine learning algorithms, namely Random Forest, Support Vector Regression, and XGBoost, to predict key quality attributes of powdered honey, including moisture content, HMF, density, solubility, and flowability. Model performance was assessed using accuracy, precision, recall, and F1-score metrics. An AFS-MTL approach was applied to filter out predictions that failed to meet predefined quality standards. The selected formulations were further optimised using a multi-objective optimisation framework to identify the optimal formulation. The model exhibiting the highest predictive accuracy was subsequently employed as the basis for recommending powdered honey formulations in the next stage.

3 Results and discussion

3.1 Machine Learning Model Analysis Results

This study used three main algorithms in the adaptive feature selection multitarget learning (AFS-MTL) scheme, namely random forest (RF), support vector machine (SVM), and extreme gradient boosting (XGBoost), to analyse powdered honey formulation data. The input variables (features) consisted of honey content, type and ratio of fillers (maltodextrin/MD and gum arabic/GA), drying method (spray drying and vacuum drying), temperature, drying time, and anti-caking additives (SiO_2). The observed outputs included chemical parameters (moisture content, Aw, reducing sugars, diastase enzymes, and sugar composition) and antioxidant activity (DPPH, ABTS, total phenols, and total flavonoids). The test results revealed that the SVM-RBF kernel model provided the best performance, with a prediction accuracy of 94.6%, $R^2 = 0.92$, and the lowest RMSE (0.084) compared with those of RF ($R^2 = 0.88$) and XGBoost ($R^2 = 0.90$). The SVM model has advantages in handling high-dimensional data with a limited number of samples, which is common in experimental food research. The adaptive feature selection process revealed that the variables most influential on powdered honey quality were the honey:filler ratio, filler type, and drying method, followed by drying temperature and time.

3.2 Effect of Rashio Honey and Filler

In this study, two types of fillers were used: maltodextrin (MD) and gum arab (GA). Both fillers act as drying aids that reduce stickiness during drying and improve powder recovery. However, their functional mechanisms differ because of their distinct physicochemical properties. Maltodextrin (MD) is widely used as a carrier material in spray drying because of its low viscosity and good solubility. It effectively encapsulates sugars, thereby preventing caramelization or crystallization during the drying process. Nevertheless, maltodextrin has a limited ability to protect heat-sensitive compounds such as phenolics and enzymes. The predictive analysis indicates that the synergistic combination of maltodextrin and gum arabic plays a significant role in reducing hygroscopicity while enhancing the solubility of honey powder. Maltodextrin contributes to improved thermal stability and drying efficiency, whereas gum arabic functions as a natural encapsulating and binding agent that supports the retention of honey colour and aroma. The interaction between these carriers forms a protective matrix that stabilizes honey components during the drying process. These findings are in agreement with previous studies reporting that the use of composite carrier systems improves physical stability, reduces powder stickiness, and effectively suppresses HMF formation under thermal processing conditions. Furthermore, the prediction outcomes are consistent with HoneyTech, which demonstrated that powdered honey formulations based on maltodextrin–gum arabic exhibit superior solubility, enhanced colour stability, and improved particle uniformity compared to formulations using single fillers. The chemical test values of powdered honey are presented in Table 1.

Table 1. Chemical test values of *powdered honey*.

Treatment	Moisture content (%)	Aw	HMF	Reducing sugars (%)	Diastase enzymes
GA 1:2 S	4.00%	0.371	17.63	16.88	15.79
GA 1:1,5 S	3.98%	0.393	19.16	10.37	13.64
MD 1:2 S	3.30%	0.402	25.86	10.46	13.64
MD 1:1,5 S	4.58%	0.377	27.99	11.38	12.5
GA 1:2 V	5.09%	0.364	12.79	14.76	18.75
GA 1:1,5 V	6.66%	0.408	15.14	16.17	16.67
MD 1:2 V	7.15%	0.483	21.71	13.88	20.00
MD 1:1,5 V	3.11%	0.373	24.31	14.23	21.43

Note : GA=Gum Arab, MD=Maltodextrin, (1:1.5 and 1:2 are the ratios between honey and filler), V=Vacuum drying, S=Spray drying

Table 1. shows that the chemical test values of powdered honey. Its high hygroscopicity can also lead to moisture absorption during storage, which may cause caking and reduce product stability. On the other hand, gum arab (GA) possesses superior emulsifying and film-forming capabilities, which make it an excellent encapsulating agent for bioactive compounds. GA forms a protective matrix around honey solids, reducing exposure to oxygen and heat. This property helps preserve phenolic and flavonoid compounds, which are responsible for antioxidant activity. As a result, samples with GA generally presented a lower moisture content and Aw, as well as higher antioxidant activity, than those formulated with MD. These findings are consistent with those of previous studies [6], which reported that gum arab-based formulations yield powders with better flowability, color stability, and antioxidant retention than maltodextrin-based powders do.

3.3 Effect of the Drying Method

Compared with spray drying, vacuum drying produces honey powder with superior chemical quality and antioxidant activity. This advantage is due primarily to the lower operating temperature, which minimizes the thermal degradation of heat sensitive bioactive compounds such as phenolics and flavonoids, thereby preserving their antioxidant potential [11]. The vacuum environment also limits oxygen exposure, effectively reducing oxidation and preventing the denaturation of enzymes such as diastase, which are sensitive to heat and oxidative stress. Consequently, vacuum dried honey powder retains greater nutritional integrity, enzyme activity, and antioxidant stability, making it more suitable for functional food formulations than its spray dried counterpart.

3.4 Validation of the AFS-MTL Predictive Model

The validation results demonstrate that the adaptive feature selection multitarget learning (AFS-MTL) model enhances modelling efficiency by approximately 30% compared with conventional approaches lacking feature selection. The feature selection process refines the dataset by eliminating redundant variables, allowing the model to focus on the most influential parameters affecting honey powder quality [12]. The multitarget learning structure enables simultaneous prediction of multiple quality indicators, such as moisture content, antioxidant activity, and enzyme stability, with increased accuracy. The integration of adaptive feature selection also improves computational efficiency and model generalization, ensuring consistent performance across varying datasets. The validated AFS-MTL model serves as a robust foundation for developing an intelligent decision support system that can optimize honey powder formulations within the functional food industry.

4 Conclusion

The adaptive feature selection multitarget learning (AFS-MTL) framework was effective in identifying the optimal powdered honey formulation while eliminating irrelevant features and outputs. Random Forest outperformed the other algorithms in predicting key quality parameters. The incorporation of feature selection improved formulation selection efficiency and accuracy by up to 35%. Formulations satisfied all antioxidant activity and chemical quality requirements, with the combination of 65% honey, 25% maltodextrin, and 10% gum arabic identified as the most stable. These findings indicate that AFS-MTL has strong potential for broader application in the development of efficient, accurate, and sustainable data-driven functional food products.

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