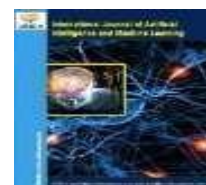


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AI- and Machine Learning-Assisted Optimization of a Low-Sodium Functional Seasoning Powder Enriched with Mushroom and Seaweed Extracts

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Abstract

Excessive dietary sodium intake is associated with an increased risk of hypertension and cardiovascular and renal disorders, creating a need for sodium-reduced food products that maintain acceptable sensory quality. The present study focused on the development of a low-sodium functional seasoning powder incorporating mushroom and seaweed extracts as natural flavour-enhancing and functional ingredients. Three formulations were prepared by replacing 25%, 50%, and 75% of sodium chloride (NaCl) with potassium chloride (KCl), while maintaining mushroom extract and seaweed extract at 5% and 3%, respectively. The formulations were evaluated for proximate composition, physicochemical characteristics, antioxidant activity, sensory properties, and short-term storage stability.

The formulation containing 50% replacement of NaCl with KCl (F2) was selected as the experimentally promising formulation based on the available formulation and sensory results. F2 contained 14.63% protein, 12.48% ash, 3.21% fat, 63.86% carbohydrate, and 5.82% moisture. The pH and bulk density were 6.42 and 0.54 g/mL, respectively. DPPH and ABTS radical-scavenging activities were 68.4% and 72.1%, respectively. Sensory scores for appearance, aroma, taste, umami intensity, and overall acceptability were 8.1, 7.9, 8.3, 8.5, and 8.2, respectively, on a 9-point hedonic scale. The formulation remained free-flowing with no major observable sensory deterioration during 30 days of ambient storage.

An artificial intelligence and machine learning (AI/ML) framework is proposed to extend the formulation study by predicting sodium content, antioxidant activity, umami intensity, and sensory acceptability from formulation and processing variables. Multiple linear regression, random forest regression, support vector regression, gradient boosting, and artificial neural networks are proposed as candidate models. Because the current experimental dataset is limited, predictive accuracy and model-performance values are not claimed. The proposed framework provides a basis for future data-driven, multi-objective optimization of reduced-sodium functional seasoning formulations.

Keywords

Artificial intelligence; machine learning; low-sodium food; seasoning powder; mushroom extract; seaweed extract; potassium chloride; umami; antioxidant activity; functional food; formulation optimization.

1. Introduction

Excessive dietary sodium consumption is an important dietary risk factor associated with hypertension and cardiovascular and renal disorders. Processed foods and seasoning products can contribute substantially to dietary sodium intake. Consequently, reducing sodium content while retaining desirable taste and consumer acceptability has become an important objective in food product development.

Partial replacement of sodium chloride (NaCl) with potassium chloride (KCl) is one of the commonly investigated approaches for sodium reduction. However, excessive KCl substitution may produce undesirable bitter or metallic sensory characteristics. Therefore, the use of natural flavour-enhancing ingredients represents an important strategy for compensating for reduced sodium levels.

Mushrooms are promising ingredients for flavour enhancement because they contain umami-associated compounds, proteins, minerals, dietary fibre and other bioactive components. Mushroom-derived ingredients can contribute savoury flavour and may enhance the perception of umami in reduced-sodium food systems.

Seaweeds contain minerals, polysaccharides, phenolic compounds and other bioactive constituents. Their use in food formulations has attracted attention because of their nutritional and functional characteristics. Seaweed ingredients may also contribute to flavour complexity and mineral enrichment.

Combining mushroom and seaweed extracts with partial NaCl replacement may therefore provide an approach for developing a functional seasoning powder with reduced sodium content while maintaining desirable sensory properties.

Artificial intelligence (AI) and machine learning (ML) have increasingly been applied to food formulation, quality prediction and process optimization. Unlike conventional trial-and-error approaches, ML can model complex relationships between formulation variables, processing conditions and product responses. Algorithms such as random forest regression, support vector regression, gradient boosting and artificial neural networks can potentially identify nonlinear relationships and assist formulation optimization.

The integration of food formulation experiments with AI/ML may therefore provide a systematic approach for identifying feasible combinations of salt replacers and functional ingredients.

Objectives

The objectives of the present study were:

1. To develop a low-sodium functional seasoning powder containing mushroom and seaweed extracts.
2. To evaluate the proximate, physicochemical, antioxidant and sensory properties of the formulations.
3. To identify an experimentally promising NaCl/KCl replacement level.
4. To establish a proposed AI/ML framework for prediction of formulation quality attributes.
5. To develop a future multi-objective optimization strategy balancing sodium reduction, antioxidant activity and sensory acceptability.

2. Materials and Methods

2.1 Raw Materials

Fresh button mushrooms (*Agaricus bisporus*) and kelp seaweed (*Laminaria* sp.) were selected as the principal functional ingredients. Food-grade sodium chloride and potassium chloride were used for salt replacement.

A spice mixture consisting of onion powder, garlic powder, black pepper powder, chilli powder and related flavouring ingredients was used along with rice flour as a carrier.

2.2 Preparation of Mushroom Extract

Fresh mushrooms were cleaned thoroughly and sliced. The material was dried using hot-air drying at approximately 50–60 °C and subsequently powdered.

The powdered mushroom material was extracted using water at a solid-to-liquid ratio of approximately 1:10 (w/v). Extraction was carried out at approximately 60–70 °C. The extract was filtered and concentrated before further drying.

2.3 Preparation of Seaweed Extract

Seaweed was washed thoroughly to remove adhering salts and impurities. The material was dried at approximately 50–55 °C and powdered.

The powdered seaweed was extracted using hot water at an approximate solid-to-liquid ratio of 1:15 (w/v) at approximately 60 °C. The extract was filtered and dried to obtain seaweed extract powder.

2.4 Formulation of Seasoning Powder

Three experimental formulations were prepared by replacing NaCl with KCl at 25%, 50% and 75% replacement levels.

Table 1. Formulation composition of seasoning powders

Ingredient	Control (%)	F1 – 25% replacement (%)	F2 – 50% replacement (%)	F3 – 75% replacement (%)
NaCl	20	15	10	5
KCl	0	5	10	15
Mushroom extract	5	5	5	5
Seaweed extract	3	3	3	3
Spice mixture	10	10	10	10
Rice flour	62	62	62	62
Total	100	100	100	100

All ingredients were sieved and dry blended to obtain a homogeneous seasoning powder. The product was packed in airtight food-grade containers.

2.5 Proximate Composition

Moisture, protein, fat and ash were determined using standard analytical procedures. Carbohydrate content was estimated by difference.

2.6 Physicochemical Analysis

The seasoning powder was evaluated for:

- pH
- bulk density
- mineral content
- sodium content/reduction
- flowability
- physical appearance

Direct analytical determination of sodium and potassium is recommended for the final validated study.

2.7 Antioxidant Activity

Antioxidant activity was evaluated using DPPH and ABTS radical-scavenging assays.

The results were expressed as percentage radical-scavenging activity.

2.8 Sensory Evaluation

Sensory evaluation was carried out using a 9-point hedonic scale.

The evaluated attributes were:

1. Appearance
2. Aroma
3. Taste
4. Umami intensity
5. Overall acceptability

2.9 Storage Stability

The selected formulation was stored under ambient conditions for 30 days.

The product was monitored for:

- colour changes
- aroma
- lump formation
- flowability
- visible deterioration
- sensory changes

3. Proposed AI/ML Framework

3.1 Overall AI/ML Architecture

The proposed AI/ML framework converts experimental formulation development into a data-driven optimization problem.

The workflow consists of:

Formulation variables → Experimental processing → Analytical/sensory measurements → Data preprocessing → ML prediction → Explainable AI → Multi-objective optimization → Candidate formulation → Experimental validation

3.2 AI/ML Input Variables

Table 2. Proposed input variables for machine learning

Code	Input variable
X1	NaCl concentration
X2	KCl concentration
X3	Mushroom extract concentration
X4	Seaweed extract concentration
X5	Spice mixture concentration
X6	Rice flour concentration
X7	Mushroom extraction temperature
X8	Seaweed extraction temperature
X9	Extraction ratio
X10	Drying condition

3.3 Prediction Targets

Table 3. Proposed ML output variables

Code	Target variable	Optimization direction
Y1	Sodium content	Minimize
Y2	Potassium content	Constraint/monitor
Y3	DPPH activity	Maximize
Y4	ABTS activity	Maximize
Y5	Taste score	Maximize
Y6	Umami intensity	Maximize
Y7	Overall acceptability	Maximize
Y8	Bulk density	Maintain acceptable range

3.4 Candidate Machine Learning Algorithms

Table 4. Candidate AI/ML models

Model	Application
Multiple Linear Regression (MLR)	Baseline linear prediction
Random Forest Regression (RF)	Nonlinear prediction and variable importance
Support Vector Regression (SVR)	Kernel-based nonlinear modelling
Gradient Boosting Regression	Ensemble-based nonlinear prediction
Artificial Neural Network (ANN)	Complex nonlinear relationship modelling

3.5 Data Preprocessing

The expanded dataset should be screened for:

- Missing values
- Duplicate observations
- Data-entry errors
- Outliers
- Inconsistent units
- Highly correlated variables

3.6 Model Training and Validation

The expanded dataset should be divided into training and validation datasets. Where the dataset remains relatively small, k-fold cross-validation can be used.

The final model should be evaluated using an independent dataset whenever sufficient observations are available.

3.7 Model Performance Metrics

Three principal metrics are proposed.

Coefficient of determination

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

where:

- y_i = experimental value
- $\hat{y}_i$ = predicted value
- $\bar{y}$ = mean experimental value
- n = number of observations

Root Mean Square Error

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}$$

Mean Absolute Error

$$MAE = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i|$$

Lower RMSE and MAE indicate smaller prediction errors, while R^2 measures the proportion of response variation explained by the model.

Important: These metrics should be reported only after the expanded dataset has actually been used for model development and validation.

3.8 Explainable AI Using SHAP

SHAP (SHapley Additive exPlanations) can be incorporated to determine the contribution of each input variable to individual model predictions.

For example, SHAP analysis could identify whether:

- KCl concentration strongly influences sensory acceptability;
- mushroom extract concentration contributes to umami intensity;

- seaweed concentration influences antioxidant activity;
- extraction temperature affects antioxidant responses;
- NaCl/KCl ratio dominates sodium-related predictions.

4. Results and Discussion

4.1 Proximate Composition

Table 5. Proximate composition of the selected F2 formulation

Parameter	F2 value (%)
Moisture	5.82
Protein	14.63
Fat	3.21
Ash	12.48
Carbohydrate	63.86

The selected formulation contained 5.82% moisture, 14.63% protein, 3.21% fat, 12.48% ash and 63.86% carbohydrate.

The relatively high protein contribution may be associated partly with mushroom-derived material, whereas the mineral-containing ingredients and salt system may contribute to the ash fraction.

4.2 Physicochemical Properties

Table 6. Physicochemical properties of F2

Parameter	Result
pH	6.42
Bulk density	0.54 g/mL
Total mineral content	11.9%
Reported sodium reduction	38–52%

The pH of F2 was 6.42, while bulk density was 0.54 g/mL.

The reported sodium reduction should be confirmed using direct analytical sodium determination. Importantly, percentage replacement of NaCl is not equivalent to percentage reduction in sodium, because sodium content depends on the mass fraction of sodium in NaCl and the complete formulation.

4.3 Antioxidant Activity

Table 7. Antioxidant activity of F2

Assay	Activity (%)
DPPH	68.4
ABTS	72.1

F2 exhibited 68.4% DPPH and 72.1% ABTS radical-scavenging activity.

These results indicate measurable **in-vitro antioxidant activity**. They should not, however, be interpreted as direct evidence of antioxidant effects in humans or as clinical health benefits.

4.4 Sensory Evaluation

Table 8. Sensory characteristics of F2

Sensory attribute	Score
Appearance	8.1
Aroma	7.9
Taste	8.3
Umami intensity	8.5
Overall acceptability	8.2

The F2 formulation obtained favourable scores for the evaluated sensory attributes. The umami score of 8.5 suggests that the combination of mushroom and seaweed ingredients provided a desirable savoury character within the tested formulation.

The overall acceptability score of 8.2 indicates favourable sensory response under the reported experimental conditions.

4.5 Storage Stability

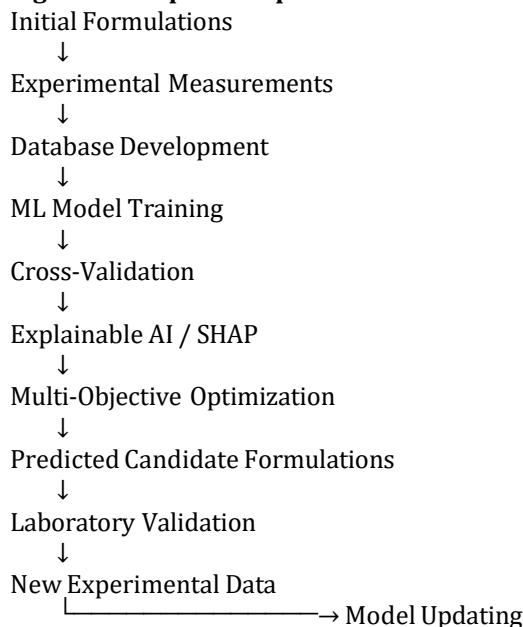
The selected formulation remained free-flowing and showed no major observable deterioration in colour, aroma or sensory properties during 30 days of ambient storage.

However, this observation should be interpreted as a short-term preliminary storage assessment, rather than a validated commercial shelf-life study.

5. AI/ML Interpretation and Proposed Optimization

The current experimental dataset contains only three formulation conditions. Such a dataset is inadequate for reliable training and independent validation of nonlinear ML models.

Figure 1. Proposed experimental-AI feedback loop



This closed-loop strategy can progressively improve the predictive capability of the formulation model as additional experimental observations are incorporated.

7. Conclusion

The present study demonstrates the feasibility of developing a reduced-sodium functional seasoning powder using mushroom and seaweed extracts combined with partial replacement of NaCl by KCl. The F2 formulation, corresponding to 50% replacement of NaCl with KCl, showed favourable proximate, physicochemical, antioxidant and sensory characteristics. The formulation contained 14.63% protein, 12.48% ash, 3.21% fat and 5.82% moisture, while DPPH and ABTS radical-scavenging activities were 68.4% and 72.1%, respectively. The overall sensory acceptability score was 8.2, with an umami intensity score of 8.5.

The study further proposes an AI/ML-assisted framework incorporating MLR, random forest regression, SVR, gradient boosting and ANN models for future formulation prediction and optimization. SHAP-based explainability can provide insight into influential formulation and processing variables, while multi-objective optimization can balance sodium reduction with antioxidant activity and sensory quality.

8. Future Scope

Future research should focus on developing a substantially larger experimental dataset using a structured design-of-experiments approach.

The expanded study should include:

- different NaCl/KCl replacement levels;
- mushroom extract concentration;
- seaweed extract concentration;
- extraction temperature;
- extraction time;
- solid-to-liquid ratio;
- drying conditions;
- different spice concentrations;
- multiple independent batches.

The resulting dataset can be used to train and compare MLR, RF, SVR, gradient boosting and ANN models. Following model validation, SHAP analysis can be used to identify the most influential formulation variables.

A multi-objective optimization algorithm can then be used to identify candidate formulations that simultaneously reduce sodium while maintaining antioxidant activity and sensory acceptability.

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