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Optimizing Quality Attributes of *Piper Retrofractum* Vahl. Through Partial Least Squares Regression: Insights from Pretreatment and Drying Experiments with Fruit Peel Infusions

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Abstract **-** The research aimed to optimize the quality attributes of *Piper retrofractum* Vahl.—piperine content, color brightness, and water content—using Partial Least Squares Regression (PLSR) to evaluate the pretreatment effects with fruit peel infusions and drying conditions. The research urgency lied in addressing the challenges of achieving consistent product quality while promoting sustainable food processing practices. Around 30 samples of *Piper retrofractum* Vahl. were subjected to varying pretreatment concentrations, soaking durations, drying durations, and peel types (orange and pineapple). The PLSR model was employed to identify key factors influencing the quality attributes and assess predictive performance based on Root Mean Squared Error (RMSE) and Coefficient of Determination (R^2) values. As a result, the PLSR model explains 43.22% of the variance in piperine content, highlighting the importance of shorter soaking durations and higher pretreatment concentrations in preserving piperine levels. For water content, the model captures 75.08% of the variance, emphasizing the critical role of drying duration in reducing moisture. However, the color brightness model explains only 18.5% of the variance, indicating the need to explore contributing factors further. The research introduces the innovative use of fruit peel-infused water as a sustainable pretreatment method, contributing to eco-friendly food processing practices and offering practical insights into optimizing production for improved product quality. The findings underscore the importance of balancing pretreatment and drying parameters to address inconsistencies in quality while promoting sustainability. Future research should expand experimental conditions, integrate additional variables, and explore advanced modeling techniques to enhance predictive accuracy and product quality.

Keywords: *Piper retrofractum* Vahl., predictive modeling in food science, Partial Least Squares Regression (PLSR), quality optimization in spice drying, sustainable food processing techniques

I. INTRODUCTION

Piper retrofractum Vahl., commonly known as Java long pepper, holds significant economic and medicinal value, especially in Southeast Asia. The plant's fruits are rich in bioactive compounds like piperine, known for its antioxidant, anti-inflammatory, and antimicrobial properties, which make it highly valuable for applications in the food, pharmaceutical, and cosmetic industries (Kubo et al., 2013; Tang et al., 2019). Traditionally, *Piper retrofractum* Vahl. has been used to treat ailments such as asthma, bronchitis, and gastrointestinal disturbances due to its carminative and stimulant properties (Dermawan et al., 2022; Panphut et al., 2020). Recently, its potential as a COVID-19 treatment has garnered attention, with studies showing promising inhibition of the virus's main protease enzyme (Supriyanto & Mojiono, 2022).

The economic relevance of *Piper retrofractum* Vahl. extends beyond its medicinal use, with its oleoresins commonly used as flavor enhancers and preservatives in food products. Furthermore, its extracts have been employed in synthesizing nanoparticles for applications in medicine and materials science, reflecting its alignment with sustainable industrial practices (Amaliyah et al., 2020, 2022). In the cosmetics industry, the plant's antioxidant properties have been explored to promote skin health and tissue regeneration, adding to its commercial appeal (Salehi, 2020).

Key quality attributes of dried *Piper retrofractum* Vahl.—piperine content, color brightness, and water content—are critical to its diverse applications. Piperine content not only determines the spice's pharmacological efficacy but also enhances its pungency, contributing to its therapeutic and culinary value (Ishii et al., 2022; Takahashi et al., 2018). However, drying processes often cause variability in piperine levels, with high temperatures potentially degrading this compound (Takahashi et al., 2018). Similarly, color brightness plays a pivotal role in consumer acceptance, as it signifies freshness and quality. Factors such as phytochemical composition and drying conditions significantly influence this attribute (Christianty et al., 2024; Oe et al., 2023; Rohmatulloh et al., 2022). Additionally, water content directly impacts the shelf life and stability of dried *Piper retrofractum* Vahl., with optimal moisture levels preventing microbial growth while maintaining flavor and medicinal properties (Ekowati et al., 2012; Gorgani et al., 2017; Nurhidayah et al., 2024; Takahashi et al., 2018).

Despite its importance, achieving consistent quality in dried *Piper retrofractum* Vahl. is challenging due to variability in processing conditions, including pretreatment and drying methods (Meechuen et al., 2023; Takahashi et al., 2018). Recent advancements suggest that fruit peel-infused water, rich in flavonoids and ascorbic acid, can enhance the preservation of piperine and color while promoting sustainability in food processing (Christianty et al., 2024; Gorgani et al., 2017; Vannabhum et al., 2023). However, the application of such eco-friendly pretreatment methods remains underexplored (Weil et al., 2017).

The research aims to optimize the quality attributes of *Piper retrofractum* Vahl. through predictive modeling using Partial Least Squares Regression (PLSR). PLSR is a robust tool capable of handling multicollinearity and multiple response variables, making it well-suited for analyzing complex datasets typical of chemometrics (Mao et al., 2023; Stark et al., 2023; Zhou et al., 2019). By leveraging PLSR, the researcher seeks to identify key factors influencing piperine content, color brightness, and water content, providing actionable insights to enhance production efficiency and product quality (Li et al., 2020; Munnaf & Mouazen, 2022).

II. METHODS

This section details the methodology used to develop a predictive model employing PLSR to assess the impact of pretreatment with fruit peel-infused water and subsequent drying conditions on the quality attributes of *Piper retrofractum* Vahl. The proposed methodology follows a systematic sequence, illustrated in Figure 1. It outlines the major stages of the experimental and analytical process. This flow diagram provides a visual representation of the steps involved, from data acquisition to predictive modeling.

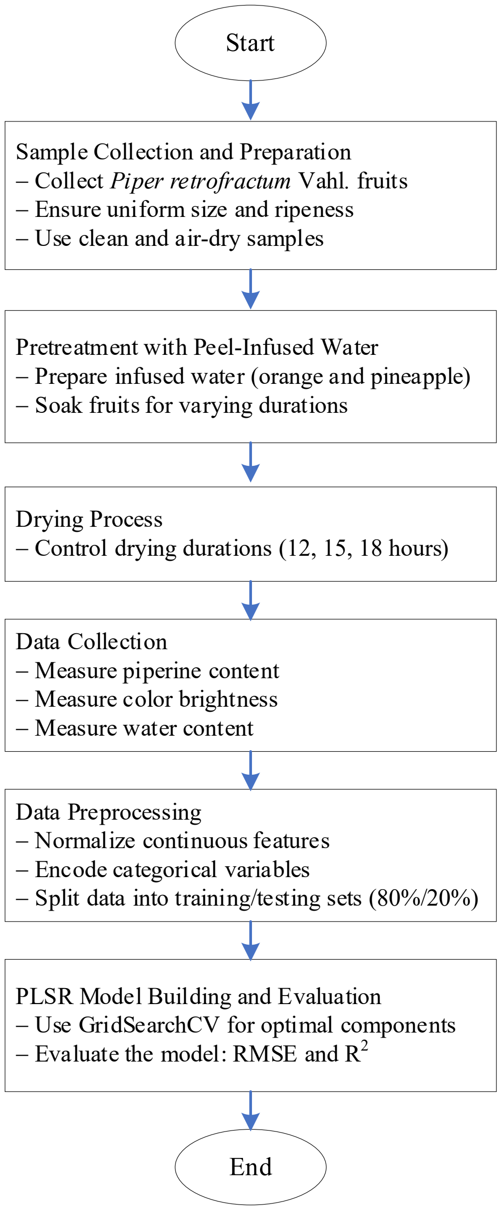

Figure 1 Research Flow Diagram, Including Partial Least Squares Regression (PLSR), Root Mean Squared Error (RMSE), and Coefficient of Determination (R^2)

The approach includes preliminary research and data collection, followed by the construction and evaluation of the PLSR model. By utilizing a structured experimental design and rigorous data analysis, the researcher aims to identify the key factors that influence the quality of *Piper retrofractum* Vahl. and to provide actionable insights for optimizing its processing conditions. The experimental data are obtained from observations intended to build a robust prediction model for these novel pretreatment methods. These observations form the foundation for developing the PLSR model, which will be used to optimize the processing conditions for *Piper retrofractum* Vahl. The experiment involves 30 samples, each with a unique combination of pretreatment concentration, soaking duration, drying duration, and peel type (orange or pineapple). This structured experimental design allowed for a comprehensive analysis of the factors affecting the quality of *Piper retrofractum* Vahl. Vahl.

At the preliminary stage, *Piper retrofractum* Vahl. fruits, selected at the half-ripe stage for uniformity in size and ripeness, are meticulously harvested. To maintain sample integrity, they are transported under controlled temperatures (10-15°C) and thoroughly cleaned with distilled water upon arrival. The fruits are then air-dried to standardize moisture levels, ensuring consistent quality and reliable experimental outcomes before undergoing pretreatment. Three specific levels of pretreatment concentration are employed using infused water from orange and pineapple peels. The low concentration consists of 750 grams of orange peels in 1,000 ml of mineral water. Then, the medium concentration involves 1,000 grams of orange peels in the same volume of water. The high concentration uses 1,250 grams of orange peels in 1,000 ml of mineral water. The soaking duration is varied across three levels to evaluate its impact on the infusion process: 3 minutes for low duration, 15 minutes for medium duration, and 30 minutes for high duration. This variation aims to assess how different soaking times influence the overall effectiveness of the infusion. Then, in the drying process, samples are oven-dried at 70°C, with the drying duration assessed at three different lengths to evaluate its effect on the final product quality. The durations tested are 12 hours for low, 15 for medium, and 18 for high.

The quality attributes of the dried *Piper retrofractum* Vahl. samples—piperine content, color brightness, and water content—are measured using precise analytical methods. High-Performance Liquid Chromatography (HPLC) is employed to determine piperine content with high accuracy, while a calibrated colorimeter is used under consistent lighting to assess color brightness. The water content is measured through a weight loss method, by weighing the samples before and after drying to calculate moisture levels. These methods ensure the reliability and accuracy of the data collected during the experimental phase.

The next stage of the research involves a comprehensive data preprocessing phase, which is crucial for ensuring the data are properly formatted for analysis. This phase begins by encoding categorical variables such as pretreatment concentration, soaking duration, drying duration, and peel type into numerical formats using techniques like One-Hot Encoding or Label Encoding. This transformation is essential to make these variables compatible with regression and neural network models, both of which require numerical input.

Following the encoding process, feature scaling is applied to the continuous features, including all dependent variables and the newly encoded categorical features. Normalization or standardization methods are employed to ensure that these features are on a consistent scale. This step is crucial as it prevents any single variable from disproportionately influencing the model due to differences in scale.

With the data appropriately scaled, the dataset is subsequently split into training and testing sets, with 80% allocated to training and the remaining 20% set aside for testing. This division is crucial for assessing the model's performance on unseen data, ensuring that the model not only fits the training data but also generalizes effectively to new examples.

Once the data are preprocessed, the next step involves building and evaluating the PLSR model. The preprocessed training and testing data are loaded from the specified files, and the dataset is separated into independent variables (features) and dependent variables (target outcomes: piperine content, color brightness, and water content) as summarized in Table 1. This separation of variables is crucial to facilitate the modeling process.

Table 1 Independent and Dependent Variables

Variable Type	Variables
Independent	Pretreatment Concentration, Soaking Duration, Drying Duration, Peel Type
Dependent	Piperine Content (%), Color Brightness (L*), Water Content (%)

A critical step in the modeling process is the selection of the optimal number of components for the PLSR model (Liu et al., 2017; Rimsha et al., 2023; Zhang et al., 2021). GridSearchCV is employed to perform a 5-fold cross-validation across a range of potential numbers of components (Salter, 2018; Tsalyuk et al., 2017). In PLSR, the components are linear combinations of the original predictors (independent variables) (Andrade et al., 2023; Khudzaifi et al., 2020). These components are derived in such a way that they maximize the covariance between the predictors and the response variable. The exact linear combinations (i.e., which predictors are involved and their respective weights) can be extracted and analyzed to understand which predictors contribute most to each component (Greenberg et al., 2023; Thelwell et al., 2020). This method allows for a thorough evaluation of different model configurations, with the optimal number of latent variables selected based on minimizing the cross-validated mean squared error (Aymen et al., 2023). The careful selection of these components ensures that the model is both accurate and efficient, balancing complexity with predictive performance (Jin et al., 2022; Wan et al., 2023).

After determining the optimal number of components, the PLSR model is fitted to the training data. It involves using the identified number of components to model the relationship between the independent variables and the target outcomes. Once the model is trained, it is used to predict outcomes on the test set, allowing for an assessment of its ability to generalize to new data.

The model's performance is assessed using essential metrics, including Root Mean Squared Error (RMSE) and the Coefficient of Determination (R^2). RMSE measures the average prediction error, indicating how closely the model's predictions match the actual outcomes (Sim et al., 2018). The R^2 offers insight into how well the model captures the variability of the data, reflecting its overall effectiveness (Yeo & Saptoro, 2024). These evaluations are critical in ensuring that the PLSR model is reliable and robust in predicting the quality attributes of *Piper retrofractum* Vahl. under various pretreatment and drying conditions.

III. RESULTS AND DISCUSSIONS

This section presents a detailed analysis and interpretation of the experimental data from the pretreatment and drying of *Piper retrofractum* Vahl. The research aims to understand how factors such as pretreatment concentration, soaking duration, drying duration, and peel type influence key quality attributes—piperine content, color brightness, and water content—using PLSR. The analysis provides valuable insights from technical, operational, and business perspectives, offering guidance on refining processing methods to optimize these quality attributes. The following sections discuss the outcomes and implications of the PLSR models in detail.

The preliminary experiment yields results from 30 samples. Each has a unique combination of pretreatment concentrations, soaking duration, drying duration, and peel type (orange or pineapple). These results, presented in Table 2, are used to model the effects on piperine content, color brightness, and water content using the PLSR model.

The PLSR analysis conducted for *Piper retrofractum* Vahl. reveals critical insights into how pretreatment and drying conditions influence key quality attributes, namely piperine content, color brightness, and water content. These findings have significant implications from technical, operational, and business perspectives. The accompanying figures visually demonstrate the predictive accuracy of the models by comparing actual versus predicted values for each target variable.

Table 2 Experimental Results

Conc	Soak	Dry.	Pip.	Col.	Wtr	Peel
Med.	Low	Low	0.295	45.02	20.49	Org
Med.	Low	High	0.539	43.2	13.54	Org
Med.	High	Low	0.49	48.02	23.72	Org
Med.	High	High	0.692	44.42	13.84	Org
Low	Med.	Low	0.651	39.66	23.60	Org
Low	Med.	High	0.796	35.03	12.03	Org
High	Med.	Low	0.661	44.26	17.50	Org
High	Med.	High	0.684	43.42	12.87	Org
Low	Low	Med.	0.207	39.95	19.38	Org
Low	High	Med.	0.439	40.72	23.97	Org
High	Low	Med.	0.283	44.66	18.85	Org
High	High	Med.	0.731	50.01	22.79	Org
Med.	Med.	Med.	0.51	44.54	20.33	Org
Med.	Med.	Med.	0.524	44.56	20.41	Org
Med.	Med.	Med.	0.518	45.3	20.55	Org
Med.	Low	Low	0.297	45.01	20.99	Pine.
Med.	Low	High	0.545	43.42	10.47	Pine.
Med.	High	Low	0.487	47.6	25.93	Pine.
Med.	High	High	0.699	41.01	14.85	Pine.
Low	Med.	Low	0.646	39.55	23.48	Pine.
Low	Med.	High	0.792	33.77	11.43	Pine.
High	Med.	Low	0.659	42.22	24.74	Pine.
High	Med.	High	0.683	40.9	11.15	Pine.
Low	Low	Med.	0.203	41.85	19.46	Pine.
Low	High	Med.	0.432	42.79	20.07	Pine.
High	Low	Med.	0.286	43.11	19.35	Pine.
High	High	Med.	0.729	44.55	21.61	Pine.
Med.	Med.	Med.	0.514	42.11	19.81	Pine.
Med.	Med.	Med.	0.521	43.79	19.80	Pine.
Med.	Med.	Med.	0.513	42.96	19.80	Pine.

Note: Conc: Pretreatment concentration (grams/ml), Soak: Soaking duration (hour), Dry.: Drying duration (hour), Pip.: Piperine content (%), Col.: Color brightness (L*), Wtr: Water content (%), Peel: Peel type (orange (org) or pineapple (Pine.)), Med.: Medium concentration, Low: Low concentration, and High: High concentration.

The PLSR model for piperine content selected seven components, achieving an RMSE of 0.0963 and an R^2 value of 0.4322. It indicates that the model captures approximately 43.22% of the variance in piperine content, reflecting moderate predictive accuracy. RMSE measures the average magnitude of the model's prediction error, where a lower value like 0.0963 suggests that predictions are reasonably close to actual values. The R^2 quantifies how well the model explains variability in the response variable. A value of 0.4322 implies that over half of the variance remains unexplained. These results are based on the selection of seven latent components in the PLSR model, chosen through five-fold cross-validation as the number that minimized prediction error. The choice of seven components indicates that the model needed a relatively complex structure to best capture the linear relationships between the predictors and piperine content, yet it still leaves room for future improvement by incorporating additional or nonlinear variables.

Figure 2 illustrates the actual versus predicted values for piperine content. It highlights the model's performance and the areas where predictions diverge from actual outcomes. The scattered points and the red dashed line representing perfect predictions ($y = x$) demonstrate the moderate fit of the model.

The weight coefficients, showing how much each predictor variable contributes to each latent component, are represented by the X-loadings in PLSR. Table 3 presents these weight coefficient values associated with the seven selected components for piperine content model. These values are computed using the Nonlinear Iterative Partial Least Squares (NIPALS) algorithm and indicate the strength and direction of each predictor's influence in forming the latent components that best explain the variation in the response variable. For example, a high positive loading for Soaking Duration (S)_Low in Component 1 (0.5315) suggests that it strongly contributes to that

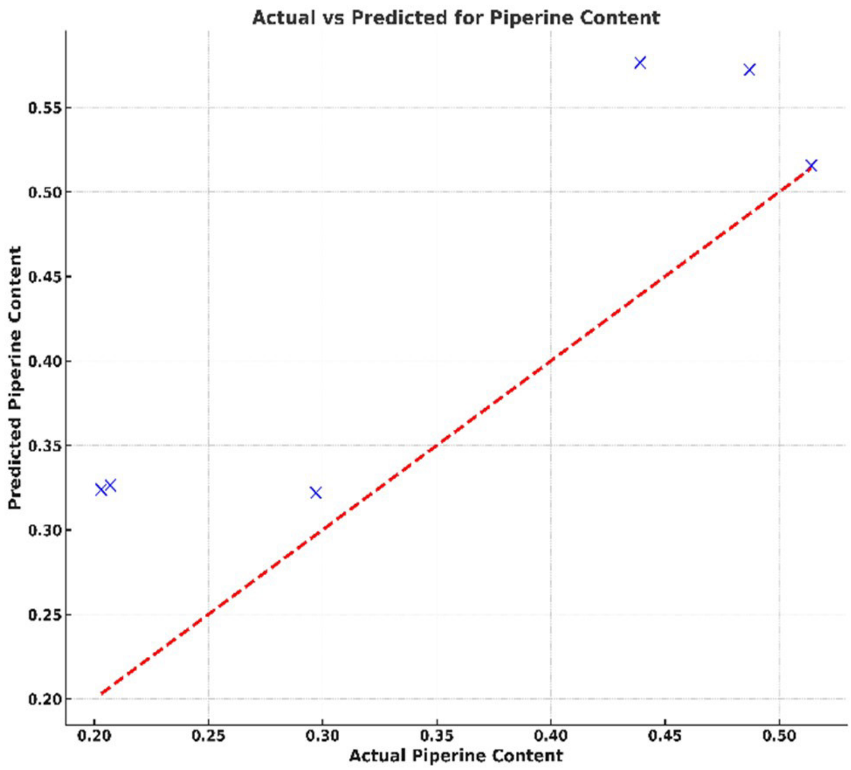

Figure 2 Actual vs Predicted Piperine Contents (%)

Table 3 Weight Coefficient Values for Piperine Content Model

	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5	Comp. 6	Comp. 7
Pretreatment Concentration (C)_High	0.01792	-0.12739	-0.56248	0.27397	0.07456	0.12771	0.52678
Pretreatment Concentration (C)_Low	-0.43515	0.44496	0.40867	0.27956	0.11089	0.08324	-0.11082
Pretreatment Concentration (C)_Medium	0.33772	-0.24215	0.19907	-0.48706	-0.16093	-0.18867	-0.40806
Soaking Duration (S)_High	-0.05554	-0.45037	0.13312	0.33458	-0.40545	0.37475	-0.16096
Soaking Duration (S)_LoW	0.53146	0.17110	0.26376	-0.02766	-0.08605	-0.21377	0.44800
Soaking Duration (S)_Medium	-0.38491	0.25193	-0.33067	-0.26822	0.42249	-0.15144	-0.22526
Drying Duration (D)_High	-0.36699	-0.29045	0.31785	-0.13850	-0.14890	-0.15190	0.29400
Drying Duration (D)_Low	-0.05625	0.34237	0.00587	-0.40492	0.02392	0.62590	0.12990
Drying Duration (D)_Medium	0.40031	-0.02298	-0.30908	0.48807	0.12136	-0.10525	-0.39519
Peel Type_Orange	0.16870	-0.36594	0.30031	-0.17104	0.54897	0.23870	0.05869
Peel Type_Pinneapple	-0.16870	0.36593	-0.30031	0.17104	-0.54890	-0.23870	-0.05869

Note: Comp.: Component.

component and is positively associated with piperine retention. These coefficients are derived to maximize the covariance between the predictors (X) and the response (Y), enabling the model to capture the most predictive structure in the data.

The following component analysis of the PLSR model for piperine content provides a detailed understanding of the interactions between various processing factors and their impact on the retention of piperine in *Piper retrofractum* Vahl. Component 1 explains the most variance in the model and highlights the critical relationship between soaking duration and pretreatment concentration. It shows that shorter soaking durations are advantageous for piperine retention, while lower pretreatment concentrations may be less effective. Specifically, there is a significant positive loading for Soaking Duration_(Low) (0.5315) and a substantial negative loading for Pretreatment Concentration_(Low) (-0.4352). This pattern indicates that shorter soaking durations help to maintain higher piperine content, likely by minimizing the potential for piperine leaching or degradation during the soaking process. In contrast, lower pretreatment concentrations appear to be less efficient in extracting piperine, possibly due to insufficient contact between the solvent and the bioactive compounds, which negatively impacts piperine levels.

Component 2 provides additional insights by highlighting the delicate balance between low pretreatment concentration and extended soaking durations. This component, characterized by a positive loading for Pretreatment Concentration_(Low) (0.4450) and a negative loading for Soaking Duration_(High) (-0.4504), suggests that while lower pretreatment concentrations may help in preserving piperine, this benefit can be undermined by extended soaking durations. Prolonged exposure to water during extended soaking likely increases the risk of piperine solubilization or degradation, leading to significant losses. This finding emphasizes the importance of carefully managing soaking times to optimize piperine retention and prevent unwanted degradation.

Component 3 introduces a new dynamic, where Pretreatment Concentration_(High) contributes negatively (-0.5625), and Pretreatment Concentration_(Low) (0.4087) and Soaking Duration_(Low) (0.2638) have positive contributions. It may reflect a saturation threshold where overly high concentrations no longer enhance extraction and can even promote instability in piperine, possibly due to increased oxidative stress or degradation facilitated by peel extracts' acidity. This component suggests a non-linear relationship where moderate conditions may be more favorable than extremes.

Component 4 reveals a complex interplay between Pretreatment Concentration_(Medium) (-0.4871), Soaking Duration_(High) (0.3346), and Drying Duration_(Low) (0.4049). The high soaking duration here contributes positively, contrasting Component 2, but only when combined with medium pretreatment and low drying time. The result suggests a contextual benefit where extended soaking paired with gentle drying may preserve piperine if the concentration is neither too strong nor too weak—highlighting the importance of multivariable interaction rather than single-factor optimization.

Component 5 shows Soaking Duration_(Medium) (0.4225) and Peel Type (Orange)_(0.5490) as key contributors. It suggests that moderate soaking times and the use of orange peel—as opposed to pineapple—may provide an optimal environment for retaining piperine, possibly due to the chemical compatibility or antioxidant properties of orange peels that stabilize piperine during drying. The higher contribution of orange peel over pineapple can also relate to enzymatic or structural differences affecting piperine's thermal stability.

Component 6 points to a dominant influence from Drying Duration_(Low) (0.6259) and Soaking Duration_(High) (0.3747). It is noteworthy because it appears to contradict earlier findings, suggesting that high soaking durations may retain piperine if followed by gentle drying. It again reinforces the idea that no single factor operates in isolation, and processing conditions must be balanced holistically.

Component 7 is particularly notable for its synergistic relationship, demonstrating that a high pretreatment concentration combined with a short soaking duration optimizes piperine retention. The synergy between Pretreatment Concentration_(High) (0.5268) and Soaking Duration_(Low) (0.4480) suggests that these conditions work together to enhance piperine extraction while minimizing degradation. This combination appears to maximize the efficiency of piperine extraction, leading to a higher yield of the desired compound. This insight is crucial for optimizing the pretreatment process, as it provides a clear strategy for achieving the best possible quality outcomes in the final product.

The complexity of the piperine content model, as indicated by the need for seven components, reflects the intricate interactions between soaking duration, pretreatment concentration, and other factors. The moderate R^2 value suggests that while the model is useful, there is potential for improvement, possibly by incorporating additional variables or exploring non-linear modeling approaches. From a technical perspective, the analysis underscores the importance of carefully balancing soaking duration and pretreatment concentration to maximize piperine yield. Operationally, it can lead to process optimizations that reduce processing time and resource use while enhancing product quality. Business-wise, the ability to produce a high-piperine product consistently can justify premium pricing and enhance market competitiveness.

Figure 3 illustrates the actual versus predicted values for color brightness. The model for color brightness selected only one component, with an RMSE of 2.3805 and an R^2 value of 0.1850. It indicates that the model explains just 18.5% of the variance in color brightness, suggesting weak predictive performance

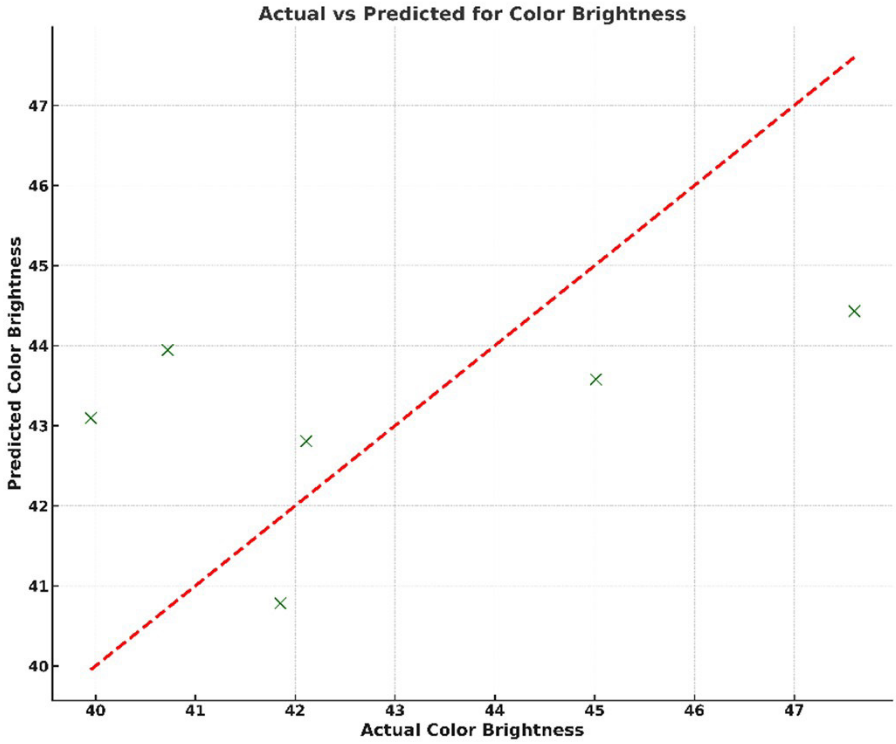

Figure 3 Actual vs Predicted Color Brightness (L*)

and the likelihood that key influencing factors are not captured. With a value of 2.3805, the RMSE suggests substantial deviations between predicted and actual color brightness values. Meanwhile, the low R^2 implies that most of the variation in brightness remains unexplained by the predictors used. These results are based on the selection of a single latent component in the PLSR model, chosen through five-fold cross-validation to minimize prediction error. The simplicity of the model structure points to limited linear relationships between the predictors and color brightness, highlighting the need for additional or more relevant variables to improve prediction accuracy.

Table 4 presents the weight coefficient values associated with the single selected latent component for color brightness model. Based on Table 4, the following component analysis of the PLSR model for color brightness analysis provides insights into the key factors influencing the visual quality of *Piper retrofractum* Vahl. after the drying process. Given that the model identifies only one significant component, it suggests a relatively straightforward relationship between the predictors and color brightness. Component 1 reveals the influence of pretreatment concentration and soaking duration on the final color outcome, highlighting the importance of these variables in maintaining or enhancing the visual appeal of the product. This single component is dominated by positive loadings for Pretreatment Concentration_(Low) (0.5160) and Soaking Duration_(Medium) (0.3835). It suggests that lower pretreatment concentrations and medium soaking durations are associated with brighter color outcomes. The lower concentration may help to prevent color dulling, while medium soaking allows for sufficient pigment extraction without over-extraction that can darken the color. This component indicates that a careful balance between these two factors is crucial for optimizing color brightness, ensuring that the product remains visually appealing, which is essential for consumer acceptance and marketability.

Table 4 Weight Coefficient Values for Color Brightness Model

	Comp. 1
Pretreatment Concentration (C)_High	-0.14770
Pretreatment Concentration (C)_Low	0.51598
Pretreatment Concentration (C)_Medium	-0.28081
Soaking Duration (S)_High	-0.25266
Soaking Duration (S)_Low	-0.20117
Soaking Duration (S)_Medium	0.38354
Drying Duration (D)_High	0.30270
Drying Duration (D)_Low	0.06431
Drying Duration (D)_Medium	-0.34591
Peel Type_Orange	-0.31477
Peel Type_Pinneapple	0.31477

Note: Comp.: Component.

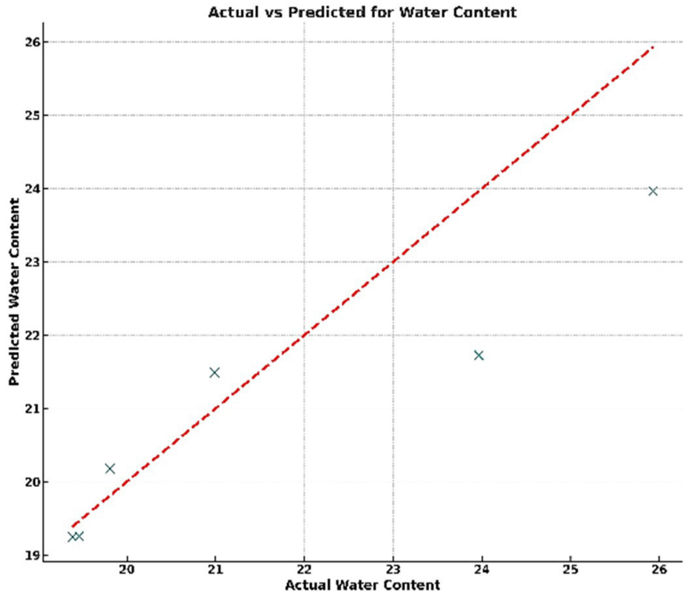

Figure 4 Actual vs Predicted Water Content (%)

Table 5 Weight Coefficient Values for Water Content Model

	Comp. 1	Comp. 2	Comp. 3	Comp. 4
Pretreatment Concentration (C)_High	-0.13165	0.49757	-0.01020	0.51236
Pretreatment Concentration (C)_Low	0.02748	-0.12862	-0.03056	-0.37669
Pretreatment Concentration (C)_Medium	0.10216	-0.36590	0.03456	-0.17771
Soaking Duration (S)_High	-0.10249	-0.29904	-0.40859	-0.16594
Soaking Duration (S)_Low	0.19247	-0.11319	0.27596	0.30088
Soaking Duration (S)_Medium	-0.06780	0.35215	0.13016	-0.10103
Drying Duration (D)_High	0.77773	0.02922	0.01517	-0.08435
Drying Duration (D)_Low	-0.39893	-0.25686	0.55782	-0.00498
Drying Duration (D)_Medium	-0.39326	0.19767	-0.50445	0.08503
Peel Type_Orange	-0.11599	0.37955	0.33557	-0.47955
Peel Type_Pinneapple	0.11599	-0.37955	-0.33557	0.47955

Note: Comp.: Component.

The simplicity of the color brightness model, with only one component and low explanatory power, indicates that the relationship between the predictors and color brightness is either straightforward or inadequately captured by the current model. The low R^2 value suggests that additional factors, such as pigment concentration or environmental conditions during drying, may play significant roles in determining color brightness. Technically, it points to the need for further research to identify these factors and improve the model. Operationally, maintaining consistent pretreatment and soaking conditions is crucial for achieving uniform color quality, which is vital for consumer acceptance. From a business perspective, optimizing color brightness can enhance product appeal and potentially justify higher pricing.

The water content model, with four latent components, performs strongly, achieving an RMSE of 1.2467 and an R^2 value of 0.7508. it indicates that the model explains 75.08% of the variance in water content, reflecting a strong linear relationship between the predictors and the outcome. RMSE represents the average deviation between predicted and actual values, and a value of 1.2467 suggests relatively low prediction error. Figure 4 shows the actual versus predicted values for water content, indicating the model's strong predictive power. The clustering of points around the diagonal line demonstrates the model's effectiveness in accurately predicting water content.

Table 5 presents the weight coefficient values associated with the four selected latent components for water content model. Based on Table 5, the following latent component analysis of the PLSR model for water content provides insights into how various factors contribute to the final moisture levels in the dried *Piper retrofractum* Vahl. The four latent components identified by the model each play a distinct role in explaining the variance in water content, highlighting the complexity of the drying process and its significant impact on the quality of the final product. Component 1 is primarily driven by the influence of drying duration, particularly when drying times are extended. With a strong positive loading of 0.7777, this component confirms the expected outcome that longer drying durations are crucial for reducing water content. The extended exposure to heat or air allows for more moisture to evaporate, resulting in a drier final product. This finding aligns with standard drying principles, where the drying duration is directly proportional to the reduction in water content.

In Component 2, the role of pretreatment concentration comes to the forefront, with a positive loading of 0.4976. Higher concentrations of the pretreatment solution appear to have a significant impact on water retention, potentially altering the peel's structural properties or influencing the efficiency of moisture removal during the drying process. It suggests that the chemical composition or concentration of the pretreatment can be fine-tuned to optimize the drying outcome, ensuring that moisture is effectively removed without compromising the quality of the peel.

Component 3 highlights the interaction between soaking duration and drying duration, with a negative loading for Soaking Duration_(High) (-0.4086) and a positive loading for Drying Duration_(Low) (0.5578). This component reflects the challenges associated with drying peels that have undergone prolonged soaking. Extended soaking increases the peel's moisture content, which, when not followed by sufficiently long drying, results in higher residual moisture in the final product. This interplay between soaking and drying durations suggests that achieving optimal water content requires a careful balance of these two processes.

Component 4 focuses on the differences between pineapple and orange peels, with a particular emphasis on pretreatment concentration. The positive loadings for Peel Type_Pineapple (0.4795) and Pretreatment Concentration_(High) (0.5124) indicate that pineapple peels, when subjected to high pretreatment concentrations, tend to retain more water. It can be attributed to the structural differences between the two types of peels, which may respond differently to the same processing conditions. Understanding these differences is crucial for tailoring the drying process to the specific characteristics of the peel type used.

The water content model's strong performance underscores the importance of drying duration as the most critical factor in reducing moisture content. The significant role of pretreatment concentration and the interaction between soaking and drying durations also highlights the need for careful optimization of these variables to achieve the desired moisture levels. Technically, the result suggests that drying processes should be precisely controlled to ensure product stability and prevent spoilage. Operationally, the ability to manage water content efficiently can lead to reduced spoilage rates, extended shelf life, and lower transportation costs due to reduced weight. From a business perspective, these efficiencies translate into cost savings and enhanced product quality, which can improve customer satisfaction and profitability.

IV. CONCLUSIONS

The research has demonstrated the significant influence of various pretreatment and drying conditions on the key quality attributes of *Piper retrofractum* Vahl. specifically focusing on piperine content, color brightness, and water content. By employing PLSR as a predictive modeling tool, the researcher has provided valuable insights into the complex relationships between these processing variables. The research offers practical implications for optimizing production processes in the food and spice industries. The findings highlight the need to balance pretreatment and drying parameters to ensure consistent product quality while supporting sustainable processing practices.

The analysis of piperine content reveals that this critical quality attribute is significantly influenced by the interaction between soaking duration and pretreatment concentration. The PLSR model, which explains 43.22% of the variance in piperine content, indicates that shorter soaking durations combined with higher pretreatment concentrations are optimal for preserving piperine levels. It suggests that prolonged soaking may lead to the degradation or leaching of piperine, while adequate pretreatment concentration ensures efficient extraction of this bioactive compound. However, the moderate R^2 value of the model implies that a substantial portion of the variance remains unexplained, pointing to the existence of additional factors or interactions that are not fully captured. This limitation highlights the need for further research to explore other variables that may affect piperine content, such as soaking temperature or the specific chemical composition of the peel extracts used in pretreatment.

In contrast, the model for color brightness is less successful, explaining only 18.5% of the variance. The analysis suggests that lower pretreatment concentrations and medium soaking durations are associated with brighter color outcomes. However, the low explanatory power of the model indicates that the predictors used may not sufficiently account for the variability in color brightness. It can be due to the influence of other factors not included in the model, such as the specific types of pigments present in the peels, variations in peel thickness, or environmental conditions during the drying process. The limitations of this model underscore the need for further investigation into the determinants of color brightness, possibly incorporating advanced analytical techniques like spectrophotometry to quantify pigment concentrations more accurately.

The analysis of water content provides a more robust model, explaining 75.08% of the variance in moisture levels. The findings emphasize that drying duration is the most critical factor in reducing water content, with longer drying times leading to lower residual moisture in the final product. The model also identifies the significant roles of pretreatment concentration and the interaction between soaking and drying durations, suggesting that these variables need to be carefully optimized to achieve the desired moisture content. The strong performance of this model underscores the importance of precise control over the drying process, which is crucial for ensuring product stability, extending shelf life, and maintaining overall quality. However, the model's reliance on specific experimental conditions limits its generalizability. Future research can explore the effects of varying drying temperatures or different types of drying methods, such as freeze-drying or vacuum drying, to enhance the understanding of moisture control in *Piper retrofractum* Vahl.

Despite the valuable insights gained, the research has several limitations that must be acknowledged. The experimental design is limited by the specific ranges of pretreatment concentration, soaking duration, and drying duration tested, which may not encompass the full spectrum of potential processing conditions. Additionally, the research focuses exclusively on orange and pineapple peels as pretreatment agents, limiting the applicability of the findings to other potential pretreatment materials. The moderate explanatory power of some models, particularly those for piperine content and color brightness, indicates that the inclusion of additional variables or the use of more sophisticated modeling techniques, such as non-linear regression or machine learning approaches, can enhance the accuracy and predictive power of the models.

Future research should aim to address these limitations by expanding the range of experimental conditions and exploring other types of fruit peels or natural extracts as pretreatment agents. Investigating the effects of different drying methods and temperatures can also provide a more comprehensive understanding of the factors influencing the quality of dried *Piper retrofractum* Vahl. Additionally, the development of more advanced predictive models, possibly incorporating machine learning techniques, can offer more accurate predictions and deeper insights into the complex interactions between processing variables. Such research will not only enhance the scientific understanding of these processes but also provide practical guidance for optimizing production methods, ultimately contributing to producing high-quality, consistent, and economically viable *Piper retrofractum* Vahl. products.

AUTHOR CONTRIBUTIONS

Conceived and designed the analysis; Collected the data; Contributed data or analysis tools; Performed the analysis; and Wrote the paper, I. L.

DATA AVAILABILITY

The author confirms that the data supporting the findings of the research are available within the article [and/or] its supplementary materials.

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