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COMPARATIVE EFFECTS OF CO-FERMENTATION AND BLENDED FERMENTATION ON THE PHYSICOCHEMICAL AND VOLATILE ORGANIC COMPOUND CHARACTERISTICS OF BANANA-FLAVORED RED RICE WINE

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ABSTRACT

This research compared how co-fermentation and blended fermentation affect the physicochemical and volatile organic compound (VOC) features of banana-flavored red rice wine made from red rice (Oryza sativa L.) and Latundan banana (Musa paradisiaca). The study was mainly focused on the differences in VOC profiles, VOC class distribution, ethanol content, pH, and VOC-derived sensory characteristics among the different treatments of fermentation. Experimenting with laboratory research design, completely randomized design was used for the study involving three treatments: co-fermentation, conventional red rice wine (control), and blended fermentation. Gas Chromatography, Mass Spectrometry (GC, MS) was employed to analyze volatile compounds, whereas pH was determined by a digital pH meter. Sensory features were inferred from VOC composition and were supported by consumer sensory evaluation through a nine-point hedonic scale. The outcomes demonstrated that the type of fermentation had a notable effect on the volatile composition and physicochemical characteristics. Blended fermentation resulted in the most varied ester profile, displayed the highest relative alcohol content, had the lowest proportion of volatile acids, and based on the predicted sensory profile was characterized by a fruity aroma and a balanced flavor. All the treatments kept pH values within the acceptable range of fermented wines. In spite of the excellent volatile composition of blended fermentation, the consumer evaluation showed a slightly higher preference for the traditional rice wine. The results show that fermentation method is very important in the production of aroma and quality of the product, and blended fermentation is one of the ways that is promising for enhancing volatile and sensory features of banana-flavored red rice wine. Moreover, these results can help in the development of fermented drinks, processing of value-added products, and innovation of agricultural products.

Keywords: Aroma development; Esterification; Fermentation strategy; Pigmented rice; Volatile organic compounds

INTRODUCTION

The global fermented beverage industry has been booming for more than ten years, mainly as a result of people becoming more aware and interested in fermented products offering various health benefits. Actually, fermentation is still regarded as one of the major ways food is made, usually resulting in products having better taste, nutrition value, longer shelf life, and profitability. Recent figures point to the global fermented food and beverage market to be worth more than $1 trillion by 2030, highlighting the fact that consumers are increasingly choosing naturally processed products not only for their distinctive flavors but also for their health benefits (Grand View Research, 2024). Of all the fermented beverages, fruit wines and cereal-based wines seem to be the most popular currently because of their rich volatile compounds, healthful ingredients, and potential for becoming new products (Adeel et al., 2022; Mishra et al., 2023). Introducing fruit-flavored rice wines can be a great way to diversify the range of traditional fermented drinks while also enhancing agricultural produce value and limiting postharvest losses.

Rice alcohols are of great cultural and economic significance all over Asia. This is particularly the case in countries, where rice is a staple product, and where

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traditional fermenting methods have long been part of the local food culture. In the production of rice wine, the starch in rice is first broken down into sugars that can then be fermented by yeast. This leads to a very complex mixture of ethanol, organic acids, esters, higher alcohols, aldehydes, and different volatile metabolites that altogether have a great impact on the quality of the product (Peng et al., 2025). More recently, research using pigmented rice varieties has started to gain momentum even outside the field of traditional rice wine production, mainly due to their better nutritional and health-beneficial properties.

It has been established that red rice has much higher levels of anthocyanins, phenolic compounds, dietary fiber, and antioxidant substances than polished white rice and therefore it can be considered as a very good raw material for the production of functional fermented beverages (Yu et al., 2023). Besides, processing red rice with the purpose of adding value corresponds to world-wide drives, which promote sustainable food systems, agricultural diversification, and the enhancement of rural livelihoods.

Fermentation systems have been continuously complemented with tropical fruits to deepen aroma complexity, improve sensory quality, and raise consumer acceptance. Banana (Musa paradisiaca) is a staple fruit among all tropical fruits and is cultivated and consumed massively all over the world. According to the Food and Agriculture Organization, global production is more than 135 million metric tons every year. Besides having a high content of fermentable sugars, they also contain organic acids, amino acids, and aroma precursors that can greatly affect fermentation and creation of volatile gaseous compounds. The main contributors to its unique smell are esters like isoamyl acetate, ethyl acetate, and ethyl butanoate, which give it wonderful fruity and floral scents. It has been shown in some recent research that the addition of fruit can trigger the activity of yeast and lead to the production of more esters and ethanol, as well as the adjustment of the sensory gains in fermented beverages. Therefore, the addition of banana to red rice wine making is a potential method for creating unique alcoholic drinks that are more attractive for the market.

The chemical and sensory properties of fermented beverages are highly influenced by volatile organic compounds (VOCs), which are fundamental factors in determining aroma, flavor, and hence the overall consumer evaluation. VOCs are produced during fermentation via several biochemical mechanisms such as carbohydrate metabolism, amino acid degradation, lipid oxidation, and esterification reactions (Styger et al., 2011; He et al., 2026). Techniques like Gas Chromatography, Mass Spectrometry (GC, MS) have become the primary method for studying these compounds thanks to their high sensitivity, precision, and capability to detect aroma-active metabolites even at very low levels (Song et al., 2018; Chucheep et al., 2026). Recent studies have highlighted the necessity to grasp how different fermentation approaches can lead to changes in the composition of VOCs because changing the fermentation conditions can greatly affect the production of esters, alcohols, acids, and other compounds associated with good or bad sensory qualities (Xu et al., 2024; Liu et al., 2023). In fact, fermentation design has been identified as one of the major determinants of microbial metabolism and the consequent flavor characteristics of alcoholic beverages made from fruits.

Among the different strategies of fermentation used in beverage production, co-fermentation and blended fermentation are the two very different ways of utilizing the substrates and developing the flavors. Co-fermentation means fermenting a few substrates at the same time, which means that microbial activities can directly interact with all the available raw materials during the whole fermentation process. On the other hand, blended fermentation means adding fruit components derived from fruits after the main fermentation, which change the composition of chemicals and the aroma of the final product, but the main fermentation pathway is not changed to a great extent. Some research works have already revealed that the fermentation strategy is a major factor determining ethanol production, ester formation, organic acid accumulation, and sensory quality in fruit wines and mixed-substrate fermented beverages (Lian et al., 2026; Wang et al., 2024). Nevertheless, results are still contradictory as to which method gives a better aroma complexity and fermentation efficiency, partly because of different substrate composition, microbial strains, and processing conditions. What is more, most of the known articles deal with grape wines, fruit wines, or traditional rice wines, and very little has been done on fruit-enhanced pigmented rice wines.

Despite the growing interest in fermented beverage innovation, there are still significant knowledge gaps concerning the influence of banana incorporation on the volatile profile and physicochemical characteristics of red rice wine. Most of the studies published so far have focused on rice wine and banana wine separately, while comparative assessments of fermentation strategies in banana-fortified red rice wine are very limited. Present research mainly concentrates on the determination of basic physicochemical parameters. On the other hand, the examination of the volatile organic compound composition and its relation to sensory properties is rarely done. Besides, there is very little information on the differential effects of co-fermentation and blended fermentation on the distribution of VOC, formation of ethanol, acidity, and aroma-active compounds in pigmented rice-based alcoholic beverages. The dearth of evidence limits the development of the most effective processing methods for value-added fermented products made from locally available agricultural commodities. Hence, a thorough study comparing these fermentation methods is required to deepen our knowledge of flavor development mechanisms and facilitate product innovation based on scientific evidence.

The importance of this study gets very clear in the Philippine scenario because the rice and banana are two of the major agricultural products of the country. The Philippines is always ranked as one of the top banana-producing countries in the world and it also has a widespread rice cultivation in different parts including Northern Luzon. Philippine Statistics Authority (2024) states that these two crops are major contributors of agricultural production, employment, and rural livelihood. The government's big push for agricultural modernization, value addition, and agribusiness development through national policies also highlight the increasing demand for farmer income improvement and postharvest loss reduction innovations. In Cagayan Province which is a production area for both red rice and banana, creating new fermented drinks will not only promote local business growth, food tourism, and sustainable use of traditional agricultural resources but will also align with the goals of the Philippine Development Plan and help in the accomplishment of Sustainable Development Goals related to food security, responsible production, and inclusive economic growth.

The present research, conducted in the context of this, explores the differential impacts of co-fermentation and blended fermentation on the physicochemical properties and volatile organic compound (VOC) characteristics of banana-flavored red rice wine produced from *Musa paradisiaca* (Latundan cultivar) and red rice. In particular, it measures changes in VOC profiles, ethanol peak ratios, pH, and VOC-derived sensory attributes by Gas Chromatography, Mass Spectrometry. The invention of this work is the direct comparison of the two fermentation strategies used on fruit-enriched pigmented rice wine system, which is a largely unexplored area in literature. By mapping the interplay between fermentation method, volatile makeup, and predicted sensory quality, the paper adds new information to the field of fermentation science, aids in the creation of value-added agricultural products, and offers handy tips to food processors, researchers, and policymakers interested in the use of and commercial value enhancement of local crops.

MATERIALS AND METHODS

Research Design

This research applied an experimental laboratory research design to investigate the differences between co-fermentation and blended fermentation in terms of the changes in physicochemical and volatile organic compound (VOC) characters of banana-flavored red rice wine. The experimental method was suitable as it gave the possibility of direct modification of the fermentation process while processing conditions for all the treatments were standardized. The research consisted of 3 experimental treatments: (1) red rice wine made by co-fermentation with banana, (2) regular red rice wine without banana (control), and (3) red rice wine made by blended fermentation with banana.

The CRD involves total randomisation of the treatment so that they are subjected to the same conditions (environment & processing) during fermenting; therefore, it allows for the measurement of how much each treatment varies from each other in terms of pH, ethanol concentration, composition of volatile organic compounds (VOCs) produced, and predicted sensory characteristics of the wine. The experimental design permitted an impartial comparison of fermentation processes and how they affect overall quality criteria of the wines.

Research Locale

This was done at the Food Innovation Center and the participating institution's designated food science labs located in Cagayan Province, Philippines. Preparation, fermentation, physicochemical analysis, and sensory evaluation of the product were carried out under controlled conditions to achieve consistent results while minimizing variation from environmental factors.

Gas chromatography-mass spectrometry (GC-MS) was performed in a qualified analytical lab with the needed equipment to carry out volatile compounds profiling. The facilities used in this project provided the technical capabilities needed to do wine production, chemical characterization, and sensory evaluation of fermented beverages.

Raw Materials and Preparation of Fermentation Substrates

Raw materials for this study were red rice (*Oryza sativa* L.) and mature Latundan bananas (*Musa paradisiaca*). Red rice was obtained from local agricultural producers in Cagayan province and the ripe bananas were bought in bulk from a local marketplace. All ripe bananas were selected so that the mature bananas were of similar degree of ripeness, did not have physical damage from handling, and showed no signs of microbial decomposition.

All rice grains were rinsed with water prior to use and were cooked according to standard procedures used to make rice wine. Bananas were peeled, blended into a homogeneous material, and prepared for addition to the fermentation system according to their treatment conditions. All equipment and materials used during the procedure were pre-sanitized prior to fermentation to reduce the chance that microorganisms would contaminate the above-mentioned products.

Experimental Treatments

Table 1: Experimental treatment matrix

Treatment	Description
T1	Co-fermentation of red rice and banana
T2	Control red rice wine without banana
T3	Blended fermentation of red rice wine and banana

Three fermentation treatments were established:

a) Treatment 1 (Co-Fermentation). Red rice and banana substrates were fermented together which allowed both substrates to be used by the microbes growing in the fermentation process at the same time.
b) Treatment 2 (Control). Conventional red rice wine made without banana added.

c) Treatment 3 (Blended Fermentation). Red rice wine was fermented first, then banana material was blended in to make a banana-flavored red rice wine.

All the treatments were conducted in identical fermentation vessels using the same inoculum levels, fermentation time, and environmental conditions to make sure that the main changes or differences that would be noticed could be mainly attributed to the fermentation strategy.

Fermentation Procedure

Prepared substrates were inoculated into a sterilized fermentation container with commercial wine yeast (*Saccharomyces cerevisiae*) and processed through fermentation under controlled ambient conditions for a specified length of time (according to specifications).

Fermentation vessels were maintained in an anaerobic state and regularly monitored for evidence of active fermentation. At the conclusion of fermentation, samples of wine were filtered to remove any remaining suspended solids. Analysis of samples for physicochemical properties and volatile compounds was then performed.

Physicochemical Analysis

Table 2. Analytical parameters evaluated

Variable	**Method**	**Purpose**
pH	Digital pH Meter	Determine acidity and fermentation stability
Ethanol Peak Ratio	GC-MS	Assess relative ethanol abundance
VOC Composition	GC-MS	Characterize aroma-related compounds
Sensory Attributes	Hedonic Evaluation	Assess product acceptability

pH Determination

The pH value for every wine sample was determined with the help of a digital pH meter that had been calibrated. Before calibration to the meter a pair of standard buffer solutions (pH 4.00 and pH 7.00) were used. The measurements were done at normal room conditions, and the obtained results were noted down as markers of wine acidity and fermentation consistency.

Ethanol Determination

Relative ethanol abundance through Gas Chromatography, Mass Spectrometry (GC-MS) analysis of were determined from the ethanol peak areas obtained from chromatograms which were used as comparative indicators of ethanol presence among treatments. Because the quantification of ethanol was based on the chromatographic peak ratios without calibration using certified ethanol standards, the results were considered as relative abundance rather than absolute alcohol concentration.

Volatile Organic Compound (VOC) Analysis

The analysis of volatile organic compounds (VOCs) was done using GC-MS. Before analyzing the samples, wine sample preparation was carried out according to standard laboratory procedures for extraction of volatile compounds.

The GC-MS system was operated using recommended analytical conditions from the manufacturers. The chromatographic separation of these samples allowed for the identification of the main VOC classes, which include esters, alcohols, and organic acids. The identification of the VOCs was done by comparing mass spectra to reference spectra stored in established databases.

The relative peak areas were used to estimate the percentage of VOC classes. Once compounds were identified, they were divided into groups based on their sensory properties and fermentation value.

Sensory Characterization

VOC-Based Sensory Prediction

By evaluation of the identified volatile organic compounds, predictions of the sensory characteristics were made. By reviewing the sensory contributions of esters, alcohols and organic acids as discussed in the existing literature on fermentation and wine chemistry, aroma and flavour descriptors were assigned. According to the existing literature, esters were indicated as contributors to fruity and floral aroma, alcohols were indicated as contributors to body or mouthfeel, while acids were indicated as contributors to sourness and to the perception of sharpness of flavour. Thus, these evaluations provide the chemical rationale for the sensory implications of fermentation treatments.

Consumer Sensory Evaluation

At the Food Innovation Center, a sensory assessment took place based on wine selections to determine participant's acceptability to certain wines and their desire to be part of this evaluation. All participants recruited were chosen based on their willingness to participate in the evaluation along with no known sensitivities to fermented foods.

All samples were presented in coded containers so as not to cause any bias towards the evaluators. Evaluators evaluated color, clarity, aroma, taste/flavours, sweetness, bitterness, mouthfeel, aftertaste, and astringency of the wine sample using a nine-point hedonic scale (with the higher scores assigned to methods indicating preferences).

Ethical Considerations

The study followed institutional ethical guidelines for food sensory evaluation. Participation was voluntary and all evaluators gave informed consent to participate before beginning sensory evaluation.

All participants were informed of the purpose of the study, how they would be evaluated as part of the study, and that they could withdraw from the study at any time without penalty. Data from evaluators did not contain any personal identifiers in order to protect confidentiality and anonymity. All data were secured and only used for research purposes.

Statistical Treatment of Data

Statistical analyses of the information collected about the samples of wines included descriptive statistics to allow for a summary of the wine samples' physicochemical and sensory characteristics.

Measurements for pH values, ethanol peak ratios, and volatile organic compounds were expressed as numerical values, percentages, and descriptive comparative analyses. The relative proportions of alcohols, acids, and esters were calculated from the GCMS corresponding to the areas under the peaks of the chromatographic profile.
Descriptive statistics were used in the sensory evaluation to ascertain the degree of acceptability by consumers on each of the attributes that were rated. A higher descriptive statistic indicates a greater level of preference by consumers for that particular attribute.
In the case of treatment comparisons, an analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$ is suggested to measure whether or not there exists a significant difference among the fermentation treatments being compared. Where there is demonstrated to be a significant difference among the fermentation treatments, a post hoc statistical method such as Tukey's Honest Significant Difference (HSD) may be performed to differentiate the specific treatment(s) which differ from each other.

RESULTS AND DISCUSSION

Physicochemical Characteristics of Banana-Flavored Red Rice Wine

Volatile Organic Compound Profiles as Influenced by Fermentation Strategy

The organic compounds (VOCs) volatilized and identified by GC, MS analysis were briefly divided into esters, acids, and alcohols, which are the main aroma, flavor, and quality contributors of wines (see Table 1). The VOC profiles were very different among the fermentation treatments showing that not only the type of fermented matter but also fermentation method can influence the metabolic activities and production of volatiles.

Table 3. Major Volatile Organic Compound Classes Identified in Banana-Flavored Red Rice Wine

VOC Class	Co-Fermentation	Control	Blended Fermentation
Esters	Ethyl acetate, ethyl butanoate, ethyl hexanoate, butyl acetate, β-phenylethyl butyrate	Ethyl acetate, ethyl butanoate, butyl butanoate	Ethyl acetate, isoamyl acetate, ethyl hexanoate, diethyl succinate, phenethyl acetate
Acids	Acetic acid, butanoic acid, hexanoic acid, propanoic acid derivatives	Butanoic acid, hexanoic acid, octanoic acid	Acetic acid
Alcohols	Ethanol, isoamyl alcohol, isobutanol, phenethyl alcohol	Ethanol, isopropyl alcohol, isoamyl alcohol	Ethanol, isobutanol, isoamyl alcohol, phenethyl alcohol

It was the blended fermentation treatment that showed the widest variety of VOCs, especially esters. Some of the ester compounds responsible for the wine aroma such as isoamyl acetate, ethyl hexanoate, and phenethyl acetate were found only in this treatment or were highly represented. Esters are the main source of fruity, floral, and sweet flavors of fermented beverages. On the other hand, the control treatment was found to contain a lesser number of ester compounds but a more varied range of volatile acids, which probably led to a less complex aroma profile.
Blended fermentations produced a wider range of esters than single fermentation processes, indicating that adding banana-derived substrates during the time following fermentation increased the available precursors for esterification. The lower levels of volatile acids also indicate that there was a more efficient conversion of acids to aroma active esters. This shows how the fermentation strategy impacts the metabolic pathways that are responsible for the formation of aroma compounds, affecting the overall chemical quality of the wine.
Our current results align with previous research indicating that the incorporation of fruit into fermentations increases the synthesis of esters by adding more fermentable sugars, amino acids, and aroma precursors which lead to an increase in yeast metabolism. Additionally, Li et al., (2023) reported that fermentation methods affect the volatile and aromatic components of mixed-substrate wines. The higher level of esters produced in blended fermentation also supports recent studies showing that fruit-based fermented products typically produce more aromatic complexity than cereal-only fermented products. The higher levels of acid in the control treatment are also consistent with data showing that limited esterification can lead to the accumulation of acids and a lower sensory appeal (Dartora et al., 2023).

Distribution of Major VOC Classes

To further characterize the influence of fermentation strategy, the relative distribution of esters, acids, and alcohols was quantified from GC–MS peak areas.

Table 4. Percentage Distribution of VOC Classes

VOC Class (%)	Co-Fermentation	Control	Blended Fermentation
Esters	40.96	35.57	40.96
Acids	54.69	63.05	3.59
Alcohols	4.35	1.38	55.46

Distinct variations in the volatile composition between blended fermentation (highest alcohol percentage) and control (highest acid percentage) were found throughout the treatments. There was a significant difference between blended fermentation (more esters produced & the least acidity) and blended acid (more acids). The excessive volume of alcohol produced during blended fermentation indicates that yeast had a greater amount of energy available to metabolize and had greater availability of resources (substrates) upon which to metabolize. The high alcohol levels provide precursors for producing esters, therefore producing esters simultaneously with alcohol. There were low amounts of organic acids available for conversion to esters during blended fermentation with the majority of acids converted to esters. Less possibility exists for producing undesirable or bad sensory/cooking notes when there is less acid to begin with. In summary, blended fermentation led to a more favourable volatile compound profile resulting in improved quality of wine.

This observed distribution pattern represents an agreement with previous studies indicating that fruit-sourced substrates stimulate ethanol and ester formation and reduce acid build-up during fermentation (Wang et al., 2023). Enhanced levels of ethanol produced as reported by Ni et al. (2026) were said to be indicative of improved fermentation efficiency and directly contributed to the amount of esters produced. The predominance of acids in the control treatment correlates with the results of a recent report that states that a lack of esterification can create volatile fatty acids that can hinder the quality of beverages.

Ethanol Abundance as Influenced by Fermentation Method

Ethanol peak ratios obtained from GC–MS chromatograms were used as comparative indicators of relative ethanol abundance among treatments.

Table 5. Ethanol Peak Ratio of Banana-Flavored Red Rice Wine

Treatment	Ethanol Peak Ratio (%)
Co-Fermentation	0.282
Control	0.052
Blended Fermentation	46.703

The results revealed that different treatments had wide-ranging peak ratios for ethanol. Of the three treatments studied, blended fermentation produced the highest amount of ethanol relative to its total volume (approximately 46.703%), while both co-fermentation and control treatments showed much lower concentrations of ethanol. It is likely that by blending fermented banana fruit after fermentation, better conditions for ethanol production and retention were created than in other fermentation methods.

The increased ethanol level seen in blended fermentations could possibly be explained by the high levels of readily-fermentable sugars found naturally in bananas. These sugars would lead to increased yeast metabolism, resulting in a greater production of alcohol during fermentation. Also, the strong relationship between ethanol and ester formation found in this investigation suggests that the presence of increased ethanol allowed for esterification reactions to occur, thereby enhancing the aroma of the final products resulting from the blended fermentation process.

The results show that adding fruit helps make more ethanol because it gives yeast more fermenting material (da Silva Fernandes et al., 2022; De Gino Soares et al., 2025). These same authors also found greater amounts of ethanol produced in fermentations when fruit was included (Yuan et al., 2024). Data from Series & Series (2024) shows that even though some authors, including Series and Series, measured the amount of ethanol produced by using chromatographic peak ratios versus actual concentrations, the results of this work appear to be consistent with prior fermentation studies that relate the amount of sugar available for fermentation to the amount of ethanol produced and the resultant aroma associated with ethanol production (Series & Series, 2024).

Acidity (pH) of Banana-Flavored Red Rice Wine

Wine acidity is a critical quality parameter affecting microbial stability, fermentation performance, and sensory perception.

Table 6. pH Values of Banana-Flavored Red Rice Wine

Treatment	pH
Co-Fermentation	3.07
Control	3.26
Blended Fermentation	3.13

All treatments had pH levels that were acceptable for produced wines, indicating successful fermentations, and the products' microbial stability. Co-fermentation had the lowest pH of all three treatments at 3.07, while the control had the highest pH at 3.26. Blended fermentation had an intermediate pH value of 3.13.

The co-fermentation pH is lower due to the higher amount of volatile acids, indicating higher acid production during simultaneous fermentation using rice and banana as substrates. In contrast, blended fermentation had a balanced pH level that provided sufficient acidity to ensure product stability; however, it did not produce excessive acid accumulation. Therefore, these two treatments provided conditions favorable to microbial safety while preserving aromas and flavours within the products.

The results from this study corroborate previous reports that demonstrate fruit-derived organic acids may have an impact on the acidity of fermentations and the final pH of wine (Morata et al., 2020). The pH levels observed in this study were also within the optimal range for Saccharomyces cerevisiae activity and for wine stability. Other studies have also demonstrated that moderate acidity enhances the retention of aromas and provides a positive influence on sensory quality (Vega et al., 2025).

Predicted Sensory Characteristics Based on VOC Composition

The sensory implications of VOC composition were inferred using established aroma descriptors associated with esters, alcohols, and acids.

Table 7. Predicted Sensory Characteristics Derived from VOC Profiles

Attribute	Co-Fermentation	Control	Blended Fermentation
Aroma	Fruity, slightly acidic	Weak, acidic	Strong fruity, pleasant
Taste	Mild fruity, slightly sour	Sour, less complex	Balanced, fruity, smooth
Color	Pale yellow	Cloudy white	Lemon yellow

Blended fermentation gave a predicted sensory profile that was the most desired, with the flavor being fruity and the taste balanced, and also, the coloration was an attractive lemon-yellow. The GC, MS analysis showed that the high ester and alcohol proportions closely match these features. On the other hand, the aroma of the control treatment was predicted to be the weakest and the sourness the highest due to high acid content and limited ester abundance.

Co-fermentation revealed intermediate sensory features, where moderate fruitiness was combined with a notable level of acidity.

These results demonstrate that the composition of VOCs plays a key role in determining the sensory potential of banana-flavored red rice wine. The good ester-to-acid ratio found in blended fermentation is crucial since esters enhance fruity and floral aroma qualities whereas an excess of acids might diminish the pleasant flavor notes.

The association of plentiful esters with fruity aroma in this research is in line with the vast wine aroma literature (Ferreira et al., 2000). Isoamyl acetate and ethyl esters are among the key components of fruit-like sensory features in fermented beverages. In the same way, Cameleyre's 2021 study showed that higher levels of alcohol and esters are usually associated with improved sensory complexity and greater consumer appeal. The less desirable profile forecasted for the control treatment falls in line with literature mentioning high volatile acid levels as a source of sour and pungent sensory features.

Consumer Sensory Evaluation

To validate the predicted sensory characteristics, selected wine samples underwent consumer acceptability evaluation.

Table 6. Mean Sensory Evaluation Scores

Attribute	Control Rice Wine	Banana-Flavored Rice Wine (Blended)
Color	7.00	5.60
Clarity	7.40	6.20
Aroma	7.20	6.40
Flavor	7.20	6.40
Sweetness	6.40	5.80
Bitterness	7.00	6.60
Mouthfeel	7.00	7.00
Aftertaste	7.40	7.20
Astringency	7.40	7.20
Overall Liking	7.60	6.80

While both products received an average of more than half on the Hedonic Scale, the control rice wine had higher mean scores for each attribute, such as aroma, flavor, and overall liking. The predictive analysis by GC-MS showed that the blended fermentation had greater aromatic complexity; yet, due to its more familiar sensory profile, consumers preferred the traditional rice wine.

The difference between the two demonstrates the relationship between instrumental data and consumer perception is very complex. While it appears that there is a relationship between VOC composition and greater aromatic complexity, consumer acceptance is influenced by other factors as well, such as whether they are familiar with the product, their expectations of a product, cultural preferences and the relationship of flavour and balance in relation to aroma. Therefore, just because a chemical compound is superior in aroma does not necessarily mean the same chemical compound will result in greater overall acceptance.

This study supports findings from previous sensory studies published by Van Eck et al. (2021), which also found no correlation of consumer acceptance to instrumental measurements of aroma. The same results have been found in other studies conducted on fruit fortified wines because consumers' expectations of taste and their familiarity with the types of wine used as a base did not increase their level of interest in a wine that had greater aromatic complexity (Llamas-Molina et al., 2023). Therefore, there should be an emphasis on both chemical analytical techniques and sensory analysis in order to provide total quality assessments of fermented beverages.

This research indicates that methods of fermentation have a significant effect on the characteristics of banana-flavored red rice wine. The blended fermentation method produced the highest amount of alcohol, the greatest diversity in esters, the lowest amount of acid build-up, and predicted the most desirable sensory characteristics. Also, from this research it was determined that the incorporation of banana at the end of fermentation provided an ideal environment for esters to develop and form an aromatic profile. However, consumer evaluation indicated a preference for the traditional control wine indicating the need for consideration of both instrumental and sensory criteria when developing a fermented beverage. Overall, blended fermentation may be the best method of increasing aroma complexity and volatile composition of banana-flavored red rice wine; however, continued optimization will likely enhance consumer acceptance and commercial opportunities.

CONCLUSION

In this study researchers observed that the way in which fermented banana-red rice wine had an impact on how the wine looked and smelled, including how much was left after fermentation, and how good it tasted. When comparing both types of ways of producing the wine, we found that blending the two types of rice together resulted in a much greater variety of kinds of esters being produced, more ethanol relative to the quantity of vinegar that was produced, less vinegar being produced, and a more desirable aroma profile than by using either co-fermenting or by making a traditional rice wine. We also confirmed that the addition of banana fruit into the wine had an effect on producing compounds with aroma-producing properties and improved the complexity of flavors through better ester formation. However, consumers did slightly prefer the traditional rice wine compared to the banana-red rice wine, but the aromatically characterisation of both types of wines indicated that blended fermentation had better aromas and a greater potential for innovation with respect to product development. This study supports the growing understanding of how various types of fermentations produce volatile compounds and the different ways in which they can be used in cereal-based fermentations. Overall, blended fermentation of bananas with locally sourced red rice represents a positive technological opportunity to produce value-added fermented products from both ingredients while advancing innovation in the field of fermentation science and in the area of product development from agricultural materials.

RECOMMENDATIONS

It is recommended that food processors, researchers and agricultural entrepreneurs use blended fermentation as a method to create banana-flavored red rice wine with a higher amount of volatile compounds and more complex aromas. Additional work on optimizing the proportion of blended ingredients, length of time fermenting, choice of yeast species, and techniques used after fermentation (post-fermentation processing) is encouraged in order to improve consumer acceptability while maintaining desirable physical and chemical characteristics. Supporting the growth of developing and creating new value-added products based on the use of fruit-enhanced rice wines will increase the economic value of red rice and bananas as locally sourced crops through government agencies, research facilities, and agricultural extension programs. Future investigations should employ quantitative determination of ethanol content, increased measurement of sensory characteristics, evaluation of shelf-life, and application of advanced multivariate statistical techniques to better define the relationships between the volatile compounds generated during fermentation and consumer preferences for those products; thus, creating a stronger scientific basis for commercial production and standardisation of those products.

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