

Coffee fermentation from traditional to controlled and its impact on sensory quality: a review

Tatiana Jazmin Neyra-Vergara¹ , Oscar Melendrez-Mauriola¹ , Blanca Yorlith Cubas-Heredia¹ ,
Gaby Norelli Contreras-Ocupa¹ , Diana Maricel Herrera-Salazar¹ , Eyla Esther Diaz-Mundaca¹ ,
Ralph Stein Rivera-Botonares² , Ernesto Hernández-Martínez^{2*} 

¹Escuela Profesional de Ingeniería de Industrias Alimentarias, Facultad de Ingeniería, Universidad Nacional de Jaén. Jaén, Cajamarca, Perú

²Departamento Académico de Ingeniería de Industrias Alimentarias, Facultad de Ingeniería, Universidad Nacional de Jaén. Jaén, Cajamarca, Perú

*Corresponding author: ernesto.hernandez@unj.edu.pe

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ABSTRACT

Coffee fermentation has evolved from traditional methods, such as traditional processing methods (washed/wet, natural/dry, honey/semi-dry) with fermentation types (wet, dry, mixed), to controlled fermentations, such as carbonic maceration, induced fermentation, and biodigestive processing, to improve the sensory quality of the final product. This evolution is compounded by technological advances, such as the use of metagenomic tools for the identification of microorganisms and enzymes to accelerate mucilage degradation. This review synthesizes and compares various coffee fermentation techniques, analyzing their influence on sensory profiles. To this end, a systematic bibliographic review of 118 scientific articles published between 2014 and 2024 was conducted in databases such as ScienceDirect, Scopus, IOPscience, Springer Nature, and Dialnet, ultimately highlighting 80 relevant studies using the PRISMA method criteria. The results indicate that controlled fermentation allows for the efficient use of microorganisms such as *Saccharomyces cerevisiae*, *Candida parapsilosis*, and *Lactiplantibacillus plantarum*, which contribute to the development of complex sensory attributes in coffee, highlighting fruity, floral, sweet, and acidic notes. Factors such as time, temperature, and inoculum type have a significant impact on the sensory profile. Principal component analysis showed that the Catuí variety was the most associated with cup score, followed by Acaíá. Furthermore, it was evident that temperature and fermentation time primarily influenced Catuí Vermelho, and that the Typica and Caturra varieties exhibited similar behavior within the diagram. Together, the application of controlled fermentation and starter cultures represents a key strategy to improve quality, standardize profiles, and meet market demands.

Key words: Controlled coffee fermentation; microbial diversity; yeasts; bacteria; induced fermentation, carbonic maceration.

1 INTRODUCTION

Fermentation of coffee beans was developed in ancient times to accelerate the decomposition and separation of mucilage (Ferreira et al., 2023), which is necessary to facilitate the drying of the beans (Braga et al., 2023).

Currently, quality is highly linked to various physicochemical components associated with the development of new flavors generated during fermentation and related to sensory analysis (Ferreira et al., 2023), improving the sensory characteristics of coffee (Bressani et al., 2021b).

The growth of different microorganisms during fermentation can lead to varied sensory profiles (Bressani et al., 2021b) due to the metabolites produced during the process; thus, the perception of exotic notes from fermentation processes may be associated with specific compounds (de Melo Pereira et al., 2015).

However, a loss of predictability in the final quality of the beans is associated with a lack of control during fermentation, causing the formation of undesirable products such as butyric or propionic acid, or even mycotoxins (Ferreira et al., 2023), resulting in low-quality coffee (Bressani et al., 2021b), which represents a problem related to food safety as well as global market needs (Ferreira et al., 2023).

Therefore, to ensure the quality and safety of coffee for the industries dedicated to this industry, it is important to know the different microorganisms that act during fermentation, since they have an impact on the composition of organic acids and organoleptic acids produced during this process and can significantly influence the quality of the beverage (Da Silva et al., 2023).

The objective of this review is to compile and synthesize the available information on coffee fermentation, with emphasis on the different processing methods (washed/wet, natural/dry, honey/semi-dry) and fermentation types (wet, dry, mixed) and advanced (carbonic maceration, induced fermentation, and digestive bioprocessing), as well as to identify the different microorganisms involved in the coffee fermentation processes (yeasts, bacteria, and filamentous fungi), the organoleptic compounds that they generate, and the sensory profiles that they develop. In addition, different fermentation treatments, their results in the sensory profile of coffee, and cup scores were evaluated. Several investigations will be compared, with special attention to the factors time, temperature, and inoculum used during the process, to evaluate their impact on the sensory and chemical properties of the final beverage, and to provide a comprehensive understanding of how these factors influence the quality of coffee.

2 MATERIAL AND METHODS

This study was based on a literature review whose primary materials were research and review articles obtained from the academic databases ScienceDirect, Scopus, IOPscience, Springer Nature, and Dialnet. A systematic search was performed using the PRISMA method (González de Dios et al., 2011). The inclusion criteria were publications between 2014 and 2024, and the search strategy included the terms “coffee fermentation,” “microbial diversity of coffee,” “traditional fermentation of coffee,” “coffee fermentation and SIAF,” “coffee fermentation by honey method,” “carbonic maceration of coffee,” “coffee fermentation with genomic approaches” and “coffee fermentation with enzymes” in both English and Spanish.

A total of 118 articles were initially identified, of which 80 studies were selected after the elimination of duplicates and a review of titles and abstracts.

The exclusion criteria limited the selection to studies that addressed the post-harvest fermentation of *Coffea arabica* or *Coffea canephora* and presented data on the type of fermentation, fermentation conditions (time and temperature), predominant microorganisms, sensory profile, and cup score. In addition, works without peer review, research focused only on the design of fermentation equipment, and studies that used raw materials other than coffee were excluded.

Principal Component Analysis (PCA) was performed using the XLSTAT software trial version to generate a Principal Component Diagram between the coffee varieties and the values of cup score, fermentation time, and temperature. The values of the means of the three numerical dependent variables reported by each variety were considered; however, the processing of information from varieties that did not have complete dependent variable values was not considered in this study.

Principal Component Analysis (PCA) was selected because it allows the simultaneous evaluation of multiple quantitative variables, such as fermentation time, temperature, and cup score across different coffee varieties, enabling the identification of patterns and associations within a multidimensional space. This approach facilitates the visualization of the similarities and differences among varieties under different fermentation conditions. While PCA is suitable for this type of quantitative multivariate dataset, alternative approaches such as Correspondence Analysis or Chi-square tests could be considered in future studies, particularly for datasets with predominantly qualitative or categorical variables.

3 RESULTS

3.1 Fermentation process

Fermentation is a biochemical process that degrades mucilage (Motato-Rocha et al., 2024), affecting the sensory

profile (Lee et al., 2015). This process involves the action of hundreds of species of microorganisms, such as yeasts, bacteria, and filamentous fungi (Pereira et al., 2024), which degrade sugars, lipids, proteins, and acids through their natural enzymes, transforming them into alcohols, acids, esters, and ketones (Vásquez et al., 2022; Bressani et al., 2021b). In addition, energy (ATP) and carbon dioxide are produced during this process (Córdoba-Castro; Guerrero-Fajardo, 2016).

3.1.1 Traditional coffee processing methods and their associated fermentations

Coffee processing begins immediately after harvesting to convert the coffee cherries into green beans. Therefore, it is essential to carry out coffee fermentation within eight hours after harvesting, as uncontrolled fermentation can start after this period, which negatively impacts the quality of the final product (Wu et al., 2022).

Coffee beans consist of five layers: silver film, parchment, mucilage, pulp, and skin, which surround two ovoid seeds (i.e., endosperm). After harvesting, coffee fruits are subjected to one of three traditional fermentation processes: wet, dry, or semi-dry (Elhalis et al., 2023). In wet fermentation (also called submerged or washed processing), the skin and pulp of the coffee cherries are first removed with pulping machines, leaving the two seeds surrounded by mucilage, which is removed by submerging the beans in open tanks filled with large volumes of water, creating anaerobic conditions suitable for a high diversity of fermentative microorganisms (Elhalis et al., 2023; Pereira et al., 2024). Fermentation time varies depending on climatic conditions, ranging from 6 to 72 h (Elhalis et al., 2023).

Natural (dry) processing, where whole cherries are dried and fermentation occurs mainly through spontaneous aerobic activity, is unwashed or open fermentation. is the oldest and most straightforward method of coffee processing, involving exposure of the entire coffee cherry to the sun. The pulp is collected at night and exposed again during the day until it reaches 11% humidity, at which time the pulp will be dry enough to proceed to the extraction of the beans (Ferreira et al., 2023; Pereira et al., 2024).

This method is characterized by the simultaneous occurrence of fermentation and drying. During the natural coffee drying process, ripe cherries are spread on the ground or platforms under the sun in layers 5–10 cm thick, turned daily, piled overnight, and spread again each day until the initial moisture content of 60–65% decreases to 11–12% (Elhalis et al., 2023; Ferreira et al., 2023). This process can take 10–25 days, depending on the environmental conditions of temperature and humidity, and in some cases, solar drying can be complemented or substituted with mechanical dryers to accelerate the process (Bressani et al., 2021b; Elhalis et al., 2023). Similar evaluations of dry fermentation in specialty

coffees from Colombia confirmed these trends (Guevara et al., 2024). Additionally, Elhalis et al. (2023) mentioned that coffee beans processed by the drying method usually present high levels of glucose and fructose, which is attributed to a lower metabolism of sugars due to the predominantly aerobic conditions of the process. These conditions limit anaerobic microbial activity, allowing the accumulation of sugars during drying.

According to Pereira et al. (2024), Brazil, the largest producer of natural coffee, benefits from a dry season during harvest, which facilitates the ideal drying of coffee cherries. However, they mentioned that a relevant aspect of the debate is the use of the term “fermentation” in this method, given that aerobic microorganisms predominate in the process. The main microorganisms reported are various species of *Bacillus* and *Candida*, as well as gram-negative bacteria of the genera *Serratia*, *Enterobacter*, and *Acinetobacter*.

Honey or semi-dry processing, where part of the mucilage remains during drying, allowing fermentation to proceed under dry or mixed conditions, is a variant of dry coffee processing in which coffee husks are removed before drying, accelerating the drying process. This technique is characterized by the presence of yeasts, such as *Pichia*, *Torulaspora*, and *Rhodotorula*, probably due to exposure to sugar after the removal of the husk (Pereira et al., 2024).

The semi-dry method, initially implemented in Brazil with Arabica coffees, is recommended when selective harvesting is not possible and high quality is desired. After harvesting, the fruits are cleaned and separated by flotation (green, ripe, overripe, and partially dried). Only ripe cherries are pulped and dried to 40% moisture, and then to 13% in 10–15 days (Elhalis et al., 2023).

3.1.2 Recent advances in the coffee bean fermentation process

In addition to the three most common coffee processing methods, other specific fermentation processes have been developed, representing more recent applications, including carbonic maceration, induced fermentation, and digestive bio-processing. In addition, honey processing modifies mucilage retention and influences fermentation (Elhalis et al., 2023; Pereira et al., 2024).

Carbonic maceration is widely used in wine fermentation, but scientific research on its use in coffee fermentation remains minimal. This type of fermentation involves the injection of CO₂ to create anaerobic conditions (Pereira et al., 2024). Furthermore, according to Brioschi et al. (2021), fermentation strategies generate biochemical interactions that alter the sensory, chemical, and microbiological profiles of coffee; therefore, they consider that in the carbonic maceration technique, the control of microbial growth is a critical parameter.

Induced fermentation is a process in which yeast or other specific microorganisms are used to create anaerobic conditions inside a closed bioreactor. Yeast metabolism produces carbon dioxide (CO₂) by consuming sugars, which helps displace oxygen in the environment, creating an oxygen-free environment necessary for fermentation (Pereira et al., 2022; Pereira et al., 2024).

Pereira et al. (2022) mention that the use of an airlock at the top of the fermentation tank (bioreactor type) is key to this process, as this device allows gases generated during fermentation, such as CO₂, to escape from the tank without internal pressure build-up; while at the same time the airlock prevents the entry of outside oxygen, which ensures that the environment inside the tank remains in anaerobic conditions, since this absence of oxygen is crucial for the starter cultures to carry out the fermentation process without the interference of unwanted microorganisms, guaranteeing a more precise control over the coffee fermentation process.

Digested bioprocessed coffee is an innovative method in which coffee beans are ingested by animals such as civets (Kopi Luwak) and elephants (Black Ivory). During transit through the host's digestive system, the beans undergo a series of enzymatic, acidic, and fermentative transformations that can last between 12 and 70 h (Lee et al., 2015). The digested parchment is recovered from the droppings, and the beans are subjected to a careful process that includes washing them to remove any residue, as well as drying them completely and removing them from their outer husks, and then hand sorting them to ensure that only the best beans are used while maintaining the quality standards of digestive bio-processed coffee. This process is distinguished by its limited annual production, which ranges between 150 and 200 kg, resulting in a high-value coffee, with prices of up to 1800 USD per kg. The sensory profile is distinguished by its smoothness, nutty and chocolate notes, robust body, and less bitterness than that of traditionally processed coffee (Elhalis et al., 2023).

Significant chemical changes have been identified in beans after digestion, such as protein degradation, which contributes to reduced bitterness and improves sensory characteristics, such as smoothness and reduced bitterness (Lee et al., 2015; Elhalis et al., 2023). These factors make digestive bio-processed coffee highly valued for its rarity and distinctive quality. Similarly, high concentrations of organoleptic compounds, such as pyrazines, pyridines, pyrroles, and phenolic compounds, have been identified in bio-processed coffee beans and roasted coffee beans, which have been linked to sensory profiles that stand out for their smoothness and nutty and chocolate notes, which are distinctive characteristics of coffee subjected to this type of processing (Elhalis et al., 2023).

Coffee processed using the “honey” method, popular in countries such as Costa Rica and El Salvador, undergoes a procedure similar to semi-drying, in which the beans

are mechanically pulped, retaining a controlled amount of mucilage around the seeds, and subsequently dried naturally for 12–30 days.

Depending on the amount of pulp remaining, the beans are classified as black honey, red, yellow, or white, with percentages of pulp adhering to the beans, which influences the chemical profile of the beans and modifies the concentration of certain sugars and amino acids. In particular, higher levels of galactinol and glutamic acid have been reported in beans processed using this method, which is believed to influence flavor development during roasting (Elhalis et al., 2023). In addition, bean drying, which can be done in the sun or by mechanical methods, is crucial for reducing moisture content to 10-12%, ensuring optimal conditions for storage and subsequent threshing (Mejia-Lotero et al., 2016).

In addition, the use of tools with a genomic approach to coffee fermentation allows the identification of novel yeast and bacterial strains. Recent studies in Colombia have applied high-throughput genomic sequencing to analyze the fermentation of Arabica coffee, identifying 46 yeast species, with *Kazachstania humilis* as the dominant species and *Pichia mandshurica*, which has a positive association with cup quality. This approach enabled the correlation of microbiota with variables such as pH, sugars, and aromatic compounds and facilitated the association of particular species with sensory attributes such as fruity and floral notes. Metagenomic analysis has shown how changes in fermentation conditions influence the production of key metabolites, paving the way for controlled and standardized fermentation processes to improve coffee quality (Pothakos et al., 2020; Aswathi et al., 2022; Cruz et al., 2023).

3.2 Microbial diversity in coffee fermentation

In recent decades, the microbial ecology of wet fermentation of coffee beans has been shown to involve a wide range of microbial groups, including lactic acid bacteria, acetic acid bacteria, *Bacillus*, *Enterobacteriaceae*, yeasts, and filamentous fungi (De Oliveira et al., 2019; Elhalis et al., 2020). These organisms can be found in a variety of places, such as the surface of coffee cherries, soil, air, water, employee hands, tools, machines, and even on flying insects. It has also been observed that the microbial species present, as well as their initial load and maximum population, vary considerably depending on the region (Elhalis et al., 2023).

3.2.1 Diversity of the yeast community in coffee fermentation

Yeasts are present in almost all types of coffee fermentation processes. In the wet method, several yeast genera, such as *Saccharomyces*, *Schizosaccharomyces*, *Candida*, *Torulaspora*, *Hanseniaspora*, *Pichia*, *Debaryomyces*, *Cryptococcus*, and *Rhodotorula*, have been regularly isolated

(De Oliveira et al., 2019). The dominant yeast species in this process are *Pichia kluyveri*, *Torulaspora delbrueckii*, and *Hanseniaspora uvarum* (Motato-Rocha et al., 2024).

On the other hand, in dry processing fermentation, yeasts including *Pichia guilliermondii*, *P. ofunaensis*, *P. anomala*, *Starmerella*, *Debaryomyces hansenii*, and *Arxula adeninivorans* have been identified, the latter being the most common, reaching a maximum population of 6 log CFU/g between 14 and 18 days; while in semi-dry processing fermentation, predominant species such as *Saccharomyces bayanus*, *Saccharomyces sp*, *Pichia anomala*, *Torulaspora delbrueckii*, and *Rhodotorula mucilaginosa*, with populations ranging from 3.4 to 6.9 log CFU/g (Elhalis et al., 2023).

Yeasts have been used as starter cultures in the post-harvest processing of coffee to reduce fermentation time and modulate the chemical and sensory characteristics of beans. In addition, it has been reported that they inhibit the growth of mycotoxin-producing fungi, which contributes to the production of toxin-free food (Bressani et al., 2018; Helena et al., 2024).

Table 1 shows the different yeasts identified in the coffee fermentation processes in the wet, semi-dry, and dry treatments.

3.2.2 Diversity of the bacterial community in the coffee fermentation process

Bacteria are the most abundant microorganisms in coffee fermentation, including species such as *Enterobacter agglomerans*, *Erwinia diselyensis*, *Escherichia coli*, and *Klebsiella pneumoniae*, in addition to lactic acid bacteria and gram-positive spore-forming bacteria, such as *Bacillus subtilis* and *B. cereus* (Da Silva et al., 2023).

Lactic acid-generating bacteria are used in the elaboration of fermented products and are among the main groups that participate in the fermentation of coffee for the elimination of mucilage because of their metabolism, as they use the sugars of this layer to generate metabolites such as lactic acid, which can influence the acidity and quality of coffee (Cassimiro et al., 2022).

The selected bacteria can be used as an inoculum in fermentation to improve differentiation, uniformity, and reproducibility of results, facilitating greater control of the process (Ferreira et al., 2024a).

Table 2 shows the different bacteria identified in the coffee fermentation processes in the wet, semi-dry, and dry treatments.

3.2.3 Diversity of filamentous fungi in coffee fermentation.

According to Elhalis et al. (2023), several species of fungi have been identified during coffee fermentation, particularly in dry and semi-dry fermentation processes. However, their concentrations are typically lower in the wet process.

Table 1: Yeast identified in different coffee processing methods.

Washed (Wet processing)	Honey (Semi-dry processing)	Natural (Dry processing)
<i>Kloeckera apis apiculata</i>	<i>Kluyveromyces sp.</i>	<i>Arxula adenivorans</i>
<i>Candida guilliermondii</i>	<i>Candida ernobii</i>	<i>Debaryomyces hansenii</i>
<i>C. glabrata</i>	<i>C. fukuyamaensis</i>	<i>D. polymorphus</i>
<i>C. humilis</i>	<i>C. membranifaciens</i>	<i>Pichia guilliermondii</i>
<i>C. quercitrose</i>	<i>C. carpophila</i>	<i>P. anomala</i>
<i>C. tropicalis</i>	<i>Pichia anomala</i>	<i>P. holstii</i>
<i>C. parapsilosis</i>	<i>P. caribbica</i>	<i>P. burtonii</i>
<i>C. krusei/inconspicua</i>	<i>Hanseniaspora uvarum</i>	<i>P. ofunaensis</i>
<i>Cryptococcus albidus</i>	<i>Saccharomyces cerevisiae</i>	<i>C. parapsilosis</i>
<i>C. laurentii</i>	<i>Shizosaccharomyces sp.</i>	<i>Saccharomyces cerevisiae</i>
<i>Pichia fermentans</i>	<i>Torulaspora delbrueckii</i>	<i>Torulaspora delbrueckii</i>
<i>P. kluyveri</i>	<i>Rhodotorula mucilaginosa</i>	
<i>P. anomala</i>		
<i>P. caribbica</i>		
<i>Hanseniaspora uvarum</i>		
<i>H. opuntia</i>		
<i>H. vineae</i>		
<i>Saccharomyces cerevisiae</i>		
<i>S. marxianus</i>		
<i>Debaryomyces hansenii</i>		
<i>Torulaspora delbrueckii</i>		
<i>Rhodotorula mucilaginosa</i>		
<i>Proteus guilliermondii</i>		

Note. Adapted from Braga et al. (2023); Bravim et al. (2023); Cruz-O'Byrne et al. (2023); De Melo Pereira et al. (2014); Elhalis et al. (2023); Lee et al. (2015); Mahingsapun et al. (2022); Martínez et al. (2017); Martínez et al. (2021); Pajoy-Trujillo and Amorocho-Cruz (2024); Palacios and Huayama (2023); Pimenta et al. (2023); Prakash et al. (2022); Reis et al. (2014); Ribeiro et al. (2017); Rocha et al. (2023); Sánchez-De la Cruz and Olivares-Muñoz (2019); Wang et al. (2020a).

The main filamentous fungi found are *Aspergillus niger*, *A. terreus*, *A. nidulans*, *A. westerdijkia*, *A. tamarii*, *Penicillium crustosum*, *P. brevicompactum*, *Fusarium lateritium*, *Rhizopus sp.*, *Mucor sp.* and *Cladosporium sp.* However, the role of these fungal species in the fermentation process has not yet been studied and remains unknown (Elhalis et al., 2023).

Table 3 shows the filamentous fungi identified in the coffee fermentation processes in the wet, semi-dry, and dry treatments.

3.3 Microbial contributions to coffee fermentation

The coffee fermentation process is key to the development of the microbiota, which includes bacteria, yeasts, and fungi (Ferreira et al., 2023). These microorganisms break down the mucilage surrounding the coffee beans and produce metabolites, such as organic acids, alcohols, and other compounds that influence the sensory quality of coffee, such as flavor, aroma, and body (Elhalis et al., 2023).

3.3.1 Fermentation and degradation of mucilage

Coffee bean mucilage is mainly composed of sugars (50%), proteins (14.2%), cellulose (9.1%), and some peptides (32.2%) (Elhalis et al., 2020). During the fermentation process, microorganisms such as yeasts and bacteria (*Lactobacillus*, *Saccharomyces*, *Escherichia*, among others) transform the sugars present in the mucilage into simpler compounds, such as ethanol, lactic acid, acetic acid, and butyric acid, releasing energy in the form of ATP; this process occurs under controlled conditions of temperature and acidity and can last up to 74 hours (Puerta; Marin; Osorio, 2012).

Mucilage degradation is mainly due to the metabolic activity of these microorganisms, which hydrolyze polysaccharides (pectins) into simpler sugars, favoring their elimination and improving the sensory quality of coffee (Ferreira et al., 2023). In addition, this degradation process can be accelerated by the addition of commercial enzymes, such as pectin lyase, allowing for a more efficient and rapid

removal of mucilage without compromising the quality of coffee (Peñuela et al., 2021).

Duicela et al. (2020) emphasize that coffees fermented by the washed method, in which enzymes are applied to accelerate the degradation of mucilage, obtain higher sensory scores than natural coffees. These scores exceed 80 points in the cup, representing an opportunity in the specialty-coffee market.

3.3.2 Microbial Metabolites

Microbial metabolism during coffee fermentation generates organoleptic compounds that shape the aromatic profile of the final product. Different strains produce specific aromatic compounds, which guide their selection. Among the key compounds for this selection are acetaldehyde, ethyl acetate, isoamyl acetate, various ketones (such as 3-pentanone, acetoin, and 2,3-butanedione), and certain terpenes (linalool

and β -citronellol), which can be transferred to the coffee beans and enrich their flavor (De Melo Pereira et al., 2019; Várady et al., 2022). Consequently, coffee made from these beans presents a greater richness of fruity, floral, buttery, creamy, sweet, and citrus aromas than unfermented coffee, highlighting the impact of fermentation on the sensory characteristics of the final product (Elhalis et al., 2023).

3.3.3 Contributions of microorganisms to the flavor, aroma, and sensory quality of coffee

The fermentation process releases different aromatic organoleptic compounds and metabolites that penetrate the beans, contributing to the flavor and aroma, and intensifying the acidity and complexity of coffee (Juárez et al., 2021). These are the key factors that determine coffee quality. According to the flavor profile, coffee beverages are mainly influenced by essential characteristics such as sweetness, acidity, and

Table 2: Bacteria identified in different coffee processing methods.

Washed (Wet processing)	Honey (Semi-dry processing)	Natural (Dry processing)
<i>Lactobacillus plantarum</i>	<i>Lactobacillus sp.</i>	<i>Bacillus amyloliquefaciens</i>
<i>L. sp.</i>	<i>Bacillus cereus</i>	<i>B. sphaericus</i>
<i>L. brevis</i>	<i>B. subtilis</i>	<i>B. subtilis</i>
<i>Bacillus subtilis</i>	<i>B. megaterium</i>	<i>B. macerans</i>
<i>B. amyloliquefaciens</i>	<i>Enterobacter aerogenes</i>	<i>B. megaterium</i>
<i>Leuconostoc mesenteroides</i>	<i>E. agglomerans</i>	<i>B. cereus</i>
<i>L. citreum</i>	<i>E. cloacae</i>	<i>Pseudomonas putrefaciens</i>
<i>L. pseudomesenteroides</i>	<i>Erwinia persicina</i>	<i>P. paucimobilis</i>
<i>Lactiplantibacillus pentosus</i>	<i>E. herbicola</i>	<i>Arthrobacter sp.</i>
<i>L. plantarum</i>	<i>Lactococcus lactis</i>	<i>A. sulfonivorans</i>
<i>Klebsiella oxytoca</i>	<i>L. plantarum</i>	<i>Acinetobacter sp.</i>
<i>K. pneumoniae</i>	<i>L. brevis</i>	<i>A. pittii</i>
<i>K. ozaenae</i>	<i>Acinetobacter sp.</i>	<i>Klebsiella sp.</i>
<i>Weissella cibaria</i>	<i>A. radioresistens</i>	<i>Weissella</i>
<i>W. soli</i>	<i>Gluconobacter cerinus</i>	<i>Agrobacterium tumefaciens</i>
<i>Exiguobacterium acetylicum</i>	<i>Tatumella terrea</i>	<i>Cellulosimicrobium cellulans</i>
<i>Lactococcus lactis</i>	<i>Micrococcus lactis</i>	<i>Enterobacter cloacae</i>
<i>Levilactobacillus brevis</i>	<i>Escherichia coli</i>	<i>Erwinia dissolvens</i>
<i>Lactocaseibacillus</i>	<i>Klebsiella pneumoniae</i>	<i>Tatumella pyseos</i>
<i>Rhamnosus</i>	<i>Serratia sp.</i>	<i>Proteus mirabilis</i>
<i>Streptococcus faecalis</i>	<i>Leuconostoc mesenteroides</i>	<i>Leuconostoc holzapfelii</i>
<i>Pseudomonas</i>	<i>Pseudomona paucimobilis</i>	
<i>Pseudomona paucimobilis</i>		
<i>Flavobacterium</i>		
<i>Enterobacter dissolvens</i>		

Note. Adapted from Elhalis et al. (2023); De Carvalho Neto et al. (2018); De Oliveira et al. (2019); Ferreira et al. (2024a); Helena et al. (2024); Mahingsapun et al. (2022); Martins et al. (2020); Mejia-Lotero et al. (2016); Motato-Rocha et al. (2024); Muzaifa et al. (2019); Pimenta et al. (2023).

bitterness, while the complex aromas generated by the organoleptic compounds of coffee (pyrazines, furans, esters, ketones, aldehydes, acids, phenols, and nitrogen compounds) are responsible for their exceptional characteristics and the sensory experience they provide. These compounds are mainly produced during roasting through complex reactions, such as the Maillard reaction (Elhalis et al., 2023).

Generally, fermented coffee is perceived to have better quality than unfermented coffee; however, incomplete or excessive fermentation can generate undesirable flavors (Elhalis et al., 2023).

Table 4 details the organoleptic compounds present in fermented roasted coffee beans, grouped according to their chemical functionality (esters, alcohols, aldehydes, acids, and ketones) and associated with specific sensory profiles.

Table 5 shows the organoleptic compounds produced by the cultures of different selected yeast species in coffee beverages according to the studies conducted.

Table 6 presents the organoleptic compounds produced in yeast co-inoculation trials in coffee beverages based on the studies conducted. Table 6 contains starter cultures with two or more yeasts, unlike Table 5, which shows only one yeast.

Table 7 shows a comparative analysis of the sensory descriptors associated with the different species of microorganisms used in fermentation processes.

Based on the results obtained from the articles collected, different coffee fermentation methods were compared, including wet, dry, semi-dry, carbonic maceration, and induced fermentations. Through the analysis of previous studies, the variations in temperature, fermentation time, and predominant microorganisms in each method were evaluated, as well as their influence on the chemical composition and sensory profiles of the final beverage. This comparison allows us to identify the specific effects of each process on coffee quality, providing an integral vision of how these factors modulate the sensory and chemical characteristics of the final product.

Table 8 presents a comparative analysis of different fermentation methods for Arabica and Canephora coffee and their results in the sensory profile, highlighting predominant microorganisms and cup scores. In addition, they include different coffee varieties and parameters, such as fermentation time and temperature.

Table 3: Filamentous fungi identified in different coffee processing methods.

Washed (Wet processing)	Honey (Semi-dry processing)	Natural (Dry processing)
<i>Acremonium sp.</i>	<i>Cladosporium cladosporioides</i>	<i>Aspergillus tubingensis</i>
<i>Ascomycota</i>	<i>Fusarium lateritium</i>	<i>A. versicolor</i>
<i>Aspergillus flavus</i>	<i>F. solani</i>	<i>A. ochraceus</i>
<i>A. fumigatus</i>	<i>F. illudens</i>	<i>Rhizopus oligosporus</i>
<i>A. niger</i>	<i>F. moniliforme</i>	<i>Cladosporium cladosporioides</i>
<i>A. pseudodeflectus</i>	<i>F. nivale</i>	<i>Penicillium decumbens</i>
<i>A. sumatrense</i>	<i>Pestalotia sp.</i>	
<i>A. tubingensis</i>	<i>Paecilomyces sp.</i>	
<i>A. ochraceus</i>	<i>Penicillium minioluteum</i>	
<i>Cladosporium</i>	<i>P. roquefortii</i>	
<i>Fusarium solani</i>	<i>P. fusarium</i>	
<i>Geotrichum sp.</i>	<i>P. solitum</i>	
<i>Giberrella sp.</i>	<i>P. funiculosum</i>	
<i>Mucor</i>	<i>P. brevicompactum</i>	
<i>Nectriaceae</i>	<i>P. chrysogenum</i>	
<i>Penicillium</i>	<i>P. crustosum</i>	
<i>brevicompactum</i>		
<i>P. roseopurpureum</i>		
<i>P. crustosum</i>		
<i>P. pseudozyma</i>		
<i>P. olsonii</i>		
<i>Rhizopus sp.</i>		

Note. Adapted from Arrúa et al. (2014); Elhalis et al. (2020); Elhalis et al. (2023); Lee et al. (2016).

Table 4: Main organoleptic compounds and their sensory descriptors in fermented roasted coffee beans.

Functional group	Chemical compounds	Sensory descriptor
Esters	Ethyl 3-hydroxybutanoate	Fruity, green, grape-like
	Methyl benzoate	Phenolic, almond-like, floral
	Methyl salicylate	Wintergreen, peppermint-like
	Ethyl palmitate	Waxy, fruity, creamy, balsamic
	Furfuryl acetate	Tasty
Alcohols	Methanol	Fruit-like candy
	1-(6-Metil-2-pirazinil)	Sweet notes, fruity, caramel-like, and citrus aromas
	1-propanol	Caramel sensation, herbaceous, bitter, followed by acidity and chocolate
	Furfuryl alcohol	Notes of chocolate, red fruits, pepper, and spice notes
	2,3-butanediol	Fruity, creamy, buttery
Aldehydes	1-hexanol	Fruity and floral
	Benzaldehyde	Sweet and spicy
	2-heptanol	Herbaceous and fruity
Acids	Acetic acid	Pungent, sour, vinegar-like
	Butanoic acid, 2-methyl	Fruity, acidic, fermented
	Propanoic acid, ethyl ester	Apple, pineapple, rum, strawberry
	Citric acid Quinic acid	Fruity acidity, berry flavor, and fruity notes
	Malic acid	Bitter astringent, acidity, and fruity notes
	Oxalic acid	Acidic notes
	Chlorogenic acid	Bitter
	Lactic acid	Bitter chocolate and milky notes
	Tartaric acid	Chestnuts, almonds, woody, and spices
	Phosphoric acid	Nuts and yellow fruits
Ketones	2-butanone	Fruity, buttery, and milky
	Acetoin	Buttery, creamy, milk-like
	2,3-Pentanedione	Oily-buttery

Note. Adapted from Aswathi et al. (2023); Bernardes et al. (2024); Da Mota et al. (2020); De León et al. (2016); De Melo Pereira et al. (2019); Elhalis et al. (2020); Lee et al. (2016); Liu et al. (2019); Pazmiño-Arteaga and Ruíz-Márquez (2022); Prakash et al. (2022); Reis et al. (2014); Santacruz et al. (2020); Therdatha et al. (2023); Váradý et al. (2022).

Table 5: Organoleptic compounds produced by yeast cultures in coffee beverage.

Selected yeast	Organoleptic compounds	Source
<i>S. cerevisiae</i>	Alcohols (ethanol, glycerol, hexanol, heptanol) and organic acids (citric, acetic, succinic acids).	Bressani et al. (2021a); Bressani et al. (2021c); De Melo Pereira et al. (2014).
<i>T. delbrueckii</i>	Benzyl alcohol, phenethyl alcohol and hexanal.	Bressani et al. (2021a); Bressani et al. (2021c).
<i>Candida parapsilosis</i>	Phenethyl alcohol, hexanal and heptanol.	Bressani et al. (2021a); Bressani et al. (2021c); de Melo Pereira et al. (2014).
<i>Pichia kluyveri</i>	Phenethyl acetate, ethyl acetate, isoamyl acetate.	De Melo Pereira et al. (2014).
<i>P. fermentans</i>	Acetaldehyde, ethyl acetate, isoamyl acetate.	De Melo Pereira et al. (2014); de De Melo Pereira et al. (2015).
<i>P. guilliermondii</i>	Acetaldehyde, ethyl acetate, propyl acetate.	De Melo Pereira et al. (2014).

Table 6: Organoleptic compounds produced in co-inoculation assays of coffee beverages.

Selected yeast	Organoleptic compounds	Source
<i>S. cerevisiae</i> + <i>C. Parapsilosis</i>	Butanediol, octanal, octanoic acid, and hexanoic acid.	Bressani et al. (2021c).
<i>S. cerevisiae</i> + <i>T. delbrueckii</i>	Phenethyl alcohol, octanoic acid, and decanoic acid.	Bressani et al. (2021c).
<i>S. cerevisiae</i> + <i>P. kluyveri</i>	Phenylethanol, isoamyl acetate, ethyl octanoate.	Wang et al. (2020a); Wang et al. (2020b).
<i>C. parapsilosis</i> + <i>T. delbrueckii</i>	Pentanoic acid, heptanol, and octanal.	Bressani et al. (2021c).
<i>S. cerevisiae</i> + <i>P. fermentans</i>	Acetaldehyde, ethanol, and ethyl acetate.	De Melo Pereira et al. (2014).
<i>S. cerevisiae</i> + <i>C. parapsilosis</i> + <i>T. delbrueckii</i>	Phenethyl acetate, pentanoic acid, hexanol, methylbutanol.	Bressani et al. (2021a).

Table 7: Sensory descriptors of coffees fermented with different yeast strains.

Sensory descriptor	<i>S. cerevisiae</i>	<i>T. delbrueckii</i>	<i>C. parapsilosis</i>	<i>P. kluyveri</i>	<i>P. fermentans</i>	<i>P. guilliermondii</i>
Fruity	Prune Peach Red fruits Fruity	Yellow fruit	Fruity Yellow fruit	Lemon	Fruity Sicilian lemon	Fruity
Nut/Cocoa	Mantecoso Chocolate Dried fruit	Walnuts Chocolate	Chocolate	Walnuts Chocolate	Butter Chocolate	---
Toasted	Smoked Toasted	---	---	Smoked Toasted	---	---
Sour	Citrus	Citrus	---	---	Citric acid	---
Green	Herbaceous	Cucumber	---	---	---	Herbaceous
Spices	Spices	---	Spices	Bell pepper	---	---
Floral	Floral	---	---	---	Floral	---
Sweet	Caramel	Caramel Honey	Caramel	Caramel Honey	Velvety Vanilla Toffee Caramel	Caramel
Fermented	---	---	Wine	---	Fermented	---

Note. Adapted from Bressani et al. (2020); De Melo Pereira et al. (2014); De Melo Pereira et al. (2015); Evangelista et al. (2014); Martins et al. (2020); Martínez et al. (2021); Ribeiro et al. (2017); Wang et al. (2020a); Wang et al. (2020b).

Figure 1 shows the Principal Component Analysis (PCA) derived from the cup value, time, and fermentation temperature for each variety shown in Table 8.

4 DISCUSSIONS

The yeasts identified in traditional fermentation processes (Table 1) concerning the wet process were predominantly from the genus *Candida*, followed by *Pichia kluyveri*, *Torulaspora delbrueckii*, and *Saccharomyces cerevisiae*.

In contrast, the *Candida* and *Pichia* genera stood out in the semi-dry and dry treatments, respectively. However, *Pichia anomala*, *S. cerevisiae*, and *T. delbrueckii* were common yeast species across the three fermentation methods.

Regarding the bacteria identified in coffee fermentation processes in wet, semi-dry, and dry treatments (Table 2), corresponding to wet fermentation, *Lactobacillus brevis* was the most used, followed by *Leuconostoc mesenteroides*,

Bacillus subtilis, and *Klebsiella oxytoca*. In the semi-dry and dry treatments, only the genus *Bacillus subtilis* was prominent. *Bacillus brevis* and *Klebsiella* were the most common bacteria in the three traditional fermentation methods.

Likewise, the filamentous fungi identified in the three traditional fermentation processes (Table 3) concerning the wet process, which has a greater diversity of fungi, among which *Aspergillus flavus*, *Aspergillus niger*, *Cladosporium*, and *Penicillium*, stand out. The semi-dry process includes fungi of the genera *Fusarium* and *Penicillium*. In contrast, the dry process is dominated by species such as *Aspergillus tubingensis*, *Penicillium decumbens*, and *Cladosporium cladosporioides*. Among the microorganisms present in the three processes, the genera *Penicillium* and *Aspergillus* were prominent. No explanation was found for the fewer yeasts, bacteria, and filamentous fungi reported for dry fermentation. It is possible that the absence of a fluid medium limits mobility and reproducibility.

Table 8: Comparative analysis of coffee processing methods and fermentation types, and their impact on sensory profile and cup score

Variety	Processing method / Fermentation type / Treatment	Temperature	Time	Predominant microorganism(s)	Sensory profile	Cup score	Source
Acaía	Natural (dry processing), drying in trays	14.6-28.2 °C	36 h	<i>Saccharomyces cerevisiae</i> , <i>Candida</i> <i>parapsilosis</i> , <i>Pichia guilliermondii</i>	Caramel, fruity, herbaceous	88	Reis et al. (2014)
Catuai Vermelho	Washed (wet processing) with induced wet fermentation	---	96 h	<i>S. cerevisiae</i> and <i>Lactiplantibacillus plantarum</i>	Bitter and astringent	87.10	Borém et al. (2024)
Catuai Vermelho	Honey (semi-dry processing), stainless steel containers	21.9 °C	72 h	<i>S. cerevisiae</i> , <i>Candida parapsilosis</i> and <i>Torulospora delbrueckii</i>	Chocolate, caramel, molasses, fruity, red berries, mint, spices	86.90	Bressani (2021a) et al.
Mundo Novo	Honey (semi-dry processing), open stainless steel containers	16.5-24 °C	27 h	<i>S. cerevisiae</i>	Sweet, caramelized sugars, citrus fruits	84.92	Bressani et al. (2021b)
Catimor	Honey (semi-dry processing), polypropylene tanks	21°C	12 h	<i>S. cerevisiae</i>	Fruity tones, citric acidity, orange and lemon flavor, panela tones, and lots of cane	84.17	Palacios and Huayama (2023)
Catuai Amarelo	Natural (dry processing), drying on a terrace or in buckets	25 °C	16 h	<i>S. cerevisiae</i> , <i>Candida</i> <i>parapsilosis</i> , and <i>T. delbrueckii</i>	Caramel and fruity	84	Bressani (2018) et al.
Typica	Washed (wet processing), biogestiver vessel	20-25°C	12 h	<i>Saccharomyces sp.</i>	Dried fruits, plums, red apple	84	Sánchez-De la Cruz and Olivares-Muñoz (2019)
Catuai Vermelho	Natural (dry processing), dried in polypropylene containers	28°C	36- 288 h	<i>S. cerevisiae</i>	Medium acidity, fruity, and caramel notes	84	Pimenta (2023) et al.
Acaía	Honey (semi-dry processing)	25 °C	---	<i>S. cerevisiae</i> , <i>Pichia</i> <i>guilliermondii</i> , and <i>Candida</i> <i>parapsilosis</i>	Caramel, slightly acidic, bitter	80	Evangelista et al. (2014)
Castillo	Washed (wet processing), bioreactors	---	18 h	<i>Candida krusei/inconspicua</i>	Aromatic, sweet, spicy, citrus, herbal, chocolate fragrance/ aroma; pleasant, pronounced, tense sweetness; medium acidity; medium body	84	Pajoy-Trujillo and Amorocho- Cruz (2024)
Catuai Amarelo	Honey (semi-dry processing), polystyrene buckets	14.6-28.2 °C	16 h	<i>Candida parapsilosis</i>	Fruity, sweet, caramel, nutty, and floral	81.4	Martinez (2017) et al.
Topazio MG 1190	Self-induced anaerobic fermentation (SIAF), cylindrical polyethylene bioreactors	---	80 h	<i>Torulospora delbrueckii</i>	Aromas and flavors of citrus, caramel, honey, chocolate, and chestnut	86.50	Martinez (2023) et al.
Catuai	Natural (dry processing), sealed in closed polyethylene bags	---	72 h	<i>Torulaspora delbrueckii</i>	Caramel, fruity notes, medium body	84.80	Rocha (2023) et al.

Continue.

Table 8: Continue.

Variety	Processing method / Fermentation type / Treatment	Temperature	Time	Predominant microorganism(s)	Sensory profile	Cup score	Source
Castillo	Washed (wet processing)	16.5°C	36 h	<i>Kazachstania humilis</i>	Sweet, fruity, floral (roses), chocolate	85.25	Cruz-O'Byrne et al. (2023)
Coffee from Ache, Indonesia	Digestive bioprocessing (civet coffee)	25 °C	48 h	<i>Bacillus subtilis</i>	Scores higher than the control in terms of aroma, flavor, and body	84.33	Muzaifa (2019) et al.
Bourbon	Washed (wet processing)	25°C	36 h	<i>Hansinasporea uvarum</i> and <i>Pichia kudriavzevii</i>	Earthy, apple cider, and nutty	85.50	Elhalis (2021) et al.
Chiang Mai Coffee, China	Washed (wet processing), controlled wetting in tanks	25°C	10 h	<i>Pichia kluyveri</i> and <i>Wickerhamomyces anomalus</i>	Stone fruit, sugar cane, banana, ripe fruit, orange, apple, red grape, brown sugar, tomato, berries, honey, citrus fruits, lemon	82.4	Mahingsapun et al. (2022).
Catuí	Washed (wet processing), induced fermentation in stirred tank bioreactor	30 °C	12 h	<i>Lactobacillus plantarum</i>	Aroma with a lactic background, lactic character flavor, caramel, citrus, and fruity notes	91.5	De Carvalho Neto et al. (2018).
Catuai Vermelho	Carbonic maceration (fermentation technology), spontaneous in polypropylene plastic bags	38 °C	120 h	<i>Lactobacillus sp.</i> and <i>Leuconostoc sp.</i>	Floral and fruity	85.2	Da Silva et al. (2023)
Caturra	Natural (dry processing), in tanks	13.2-26 °C	10-20 h	Lactic acid bacteria and acetic acid bacteria	Balanced acidity	85	Córdoba-Castro and Guerrero- Fajardo (2016)
Caturra	Honey (semi-dry processing), closed tanks	25 °C	30 h	Lactic acid bacteria	High acidity	84.99	Ladino et al. (2016)
Bourbon	Washed (wet processing), induced wetting in plastic containers	29.5-35.2 °C	15 h	15% yeast	---	83.5	Caballero-Pérez et al. (2016)
Catuai Vermelho	Carbonic maceration (fermentation technology), spontaneous in polypropylene plastic bags	38 °C	120 h	Not evaluated	Acidity, butter, coconut	85.15	Brioschi et al. (2021)
Catimor	Honey (semi-dry processing), stainless steel cylinders	22-28 °C	72 h	---	---	85.08	Alomía-Lucero. et al. (2022).
Catuai Amarelo	Self-induced anaerobic fermentation (SIAF)	25 °C	87 h	---	Smooth and floral flavor, spicy and slightly caramelized, woody and spicy like cinnamon	84.83	Batista et al. (2022)

Continue.

Table 8: Continue.

	Variety	Processing method / Fermentation type / Treatment	Temperature	Time	Predominant microorganism(s)	Sensory profile	Cup score	Source
<i>Coffea arabica</i>	Typica	Washed (wet processing), spontaneous fermentation in well	25 °C	18 h	---	Floral, sweet, lemon verbená	84.75	Márquez- Romero et al. (2020).
	Catucaí	Natural (dry processing), spontaneous fermentation (dry)	10 °C	18 h	---	Rough, bitter, bitter, neutral, resabio, inconsistent, opaque	84.7	Maldonado et al. (2024)
	Catucaí	Natural (dry processing), spontaneous double dry fermentation in tanks (bioreactor)	22.8 °C	40 h	---	Characteristic notes of chocolate, orange, panela, almond, hint of raisin, honeyed citric acidity	84.25	Torres et al. (2024)
	Arara	Washed (wet processing), spontaneous fermentation in closed polyethylene bioreactors	29 °C	96 h	---	Caramel, brown sugar, honey, orange, lemon, floral, dried fruits, yellow, and red	84	Ferreira et al. (2024b)
	Caturra	Washed (wet processing), spontaneous humid fermentation	25°C	18 h	---	Tamarind flavors, pineapple, caramel, almond liqueur, vanilla, cognac, papaya, and plum	84	Juárez (2021) et al.
<i>Coffea Canephora</i>	Catucaí	Washed (wet processing)	18.3 °C	16 h	---	Red fruit and citrus flavor	79.25	Álvarez et al. (2024)
	Conilon	Self-induced anaerobic fermentation (SIAF)	25 °C	72 h	<i>S. cerevisiae</i> , <i>Meyerozyma caribbica</i> , and <i>Bacillus licheniformis</i>	Caramel, fruits, and spices	89	Cassimiro et al. (2023)
	Conilon	Washed (wet processing), induced fermentation	---	120 h	<i>S. cerevisiae</i>	Fruity and light floral, high acidity, and striking sweetness.	83.56	Zani et al. (2022)
	Conilon	Self-induced anaerobic fermentation (SIAF)	28 °C	72 h	<i>Hanseniaspora opuntiae</i>	Fruity and exotic	82	Bernardes et al. (2024)
	Robusta	Washed (wet processing), enzymatic wetting	---	25 h		Notes of fruits, nuts, spices, and sweets	81.92	Duicela et al. (2018).
	Tropical Robusta	Natural (dry processing)	25 °C	48 h		Fruity, almond	80.95	Da Silva et al. (2021)
	Conilon	Washed (wet processing), moist fermentation in polypropylene pails	22 °C	48 h				Bravim et al. (2023)

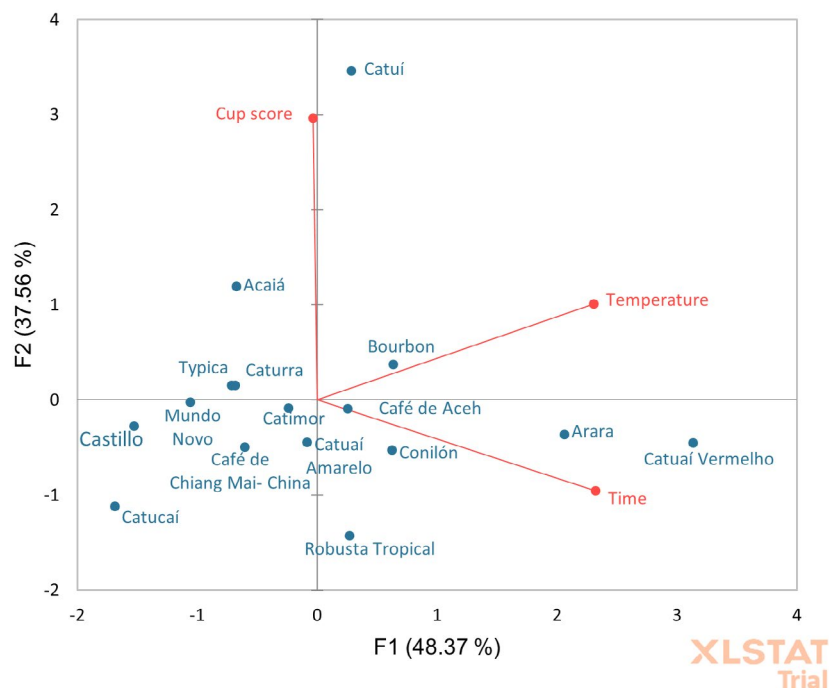


Figure 1: Principal Component Diagram between coffee varieties, cup value, temperature, and fermentation time.

Among the organoleptic compounds identified among roasted coffee beans (Table 4), as well as yeast cultures in coffee beverages (Table 5), in addition to those of co-inoculation tests in coffee beverages (Table 6), ethyl acetate, acetaldehyde, phenethyl alcohol are mentioned five times, followed by isoamyl acetate, phenethyl acetate and octanoic acid four times.

On the other hand, the sensory profiles attributed to different types of yeasts are described (Table 7), including *S. cerevisiae*, which tends to confer intense flavors to coffee that stand out for their fruity notes of plum, raisin, peach, red fruits, citrus, caramel, chocolate, dried fruits, spices, and floral notes. In contrast, strains such as *P. fermentans* tend to generate sensory profiles with predominantly floral, citrus, fruity, sweet (velvety, vanilla, toffee, and caramel), and fermented notes. Other specific sensory perceptions identified include cucumber, yellow fruit, and honey (*T. delbrueckii*), wine-like notes (*C. parapsilosis*), smoky and toasty notes (*P. kluyveri*), and herbaceous notes (*P. guilliermondii*).

This opens up the possibility for coffee producers to select specific yeast strains to produce differentiated coffees tailored to meet the demands of particular markets. However, it is crucial to consider both the fermentation method and coffee variety, as key environmental factors condition the metabolism of yeasts for their optimal development.

In the different fermentation methods (Table 8) and their results in the sensory profile of coffee, yeasts were the most used microorganisms in coffee fermentation, with *S. cerevisiae* being the most used with a total of 11 investigations, followed

by *C. parapsilosis* with six investigations, the genus *Pichia* with five investigations, *T. delbrueckii* with four investigations, and the genus *Hanseniaspora* with two investigations, followed by lactic acid bacteria with six investigations, acetic acid bacteria, and the genus *Bacillus* with two investigations.

The primary application of *S. cerevisiae* in fermentation processes is due to its extensively studied metabolism and high fermentative efficiency owing to its high pectinolytic enzyme activity, which favors efficient mucilage degradation, as well as its recognized safety profile in food applications (Elhalis et al., 2020).

The highest cup score of 91.5, from the Arabica species, was obtained with the Catuá variety through the treatment induced in an agitated tank bioreactor, in which *Lactobacillus plantarum* was inoculated with a fermentation time of 12 h at a temperature of 30 °C. This was followed by the Acaíá variety (88 points in cup) with the dry treatment in trays in which *S. cerevisiae*, *C. parapsilosis*, and *P. guilliermondii* were inoculated with a fermentation time of 36 hours at a temperature in the range of 14.6 to 28.2 °C. The Catuaí Vermelho variety (87.10 points in cup) was subjected to the induced wet treatment in which *S. cerevisiae* and *Lactiplantibacillus plantarum* were inoculated, with a fermentation time of 96 h, without temperature control. In contrast, the lowest cup score was obtained with the Catucaí variety (79.25 cup points) with the wet treatment, with spontaneous fermentation, at a time of 16 h at a temperature of 18.3 °C. This was followed by the Catuaí Amarelo variety (81.4 points in cup) with the semi-dry treatment in polystyrene buckets in which *C. parapsilosis* was

inoculated with a fermentation time of 16 h at a temperature within the range of 14.6 to 28.2 °C.

For the *canephora* species, the highest score was achieved with the self-induced anaerobic fermentation (SIAF) using the Conilon variety, which was carried out at 25 °C for 72 h, achieving 89 points in the cup and a complex sensory profile that included caramel, fruits, and spices, thanks to the synergistic interaction of *S. cerevisiae*, *Meyerozyma caribbica*, and *Bacillus licheniformis*.

Likewise, fermentation induced with the use of *S. cerevisiae* alone, in the Conilón variety, for 120 h resulted in a score of 83.56 points. These results underline that the metabolism of *S. cerevisiae* favors the production of esters and organoleptic compounds responsible for fruity and floral notes. However, using the same variety and applying the SIAF treatment at 28 °C for 72 h, in which *Hanseniaspora opuntiae* was inoculated, 82 points were achieved, which stood out for its fruity and exotic profile. This was followed by the Robusta variety, which was made without microorganism inoculation and underwent wet enzymatic treatment at 25 h, resulting in 81.92 points.

In contrast, the lowest score of 79.77 was obtained with the use of *B. licheniformis* in wet fermentation at 22 °C for 48 h in the Conilón variety, which was characterized by a more balanced profile with notes of almond, caramel, and chocolate. The dry method applied to the Robusta Tropical variety, with a “spontaneous” fermentation at 25 °C for 48 h, generated almond notes and obtained an intermediate score of 80.95.

This suggests that bacterial microorganisms may produce less complex profiles than yeasts; however, they can offer characteristics that are appealing to specific consumers.

Studies on fermentation methods indicate that controlled techniques, such as SIAF and induced fermentation, tend to produce higher cup scores than traditional wet methods.

In addition, Figure 1 shows that the cup score is more related to the Catuá and Acaíá varieties, and the least associated variety is Catuá Vermelho. Likewise, temperature and fermentation time had a greater influence on the Catuá Vermelho and Arara varieties. Finally, Typica and Caturra varieties showed very similar behaviors for the variables of time, temperature, and cup score, as shown by the practical superposition of their points in the principal component diagram.

5 CONCLUSIONS

Controlled fermentation with selected microorganisms, mainly yeasts such as *Saccharomyces cerevisiae* and *Candida parapsilosis*, promotes the development of complex fruity and floral profiles, while lactic acid bacteria enhance acidity and freshness. Induced fermentations with *Lactobacillus plantarum* have achieved up to 91.5 cup points, demonstrating that optimizing microbial selection, fermentation time,

and temperature enables reproducible sensory profiles and consistent improvement in specialty coffee quality.

6 AUTHORS' CONTRIBUTIONS

Conceptual Idea: Neyra-Vergara, T.J; Melendrez-Mauriola, O; Cubas-Heredia B.Y; Methodology design: Contreras-Ocupa G.N; Data collection: Diaz-Mundaca, E.E; Herrera-Salazar D.M; Data analysis and interpretation: Rivera-Botonares, R.S; and Writing and editing: Hernández-Martínez, E.; Neyra-Vergara, T.J; Melendrez-Mauriola, O; Cubas-Heredia B.Y; Contreras-Ocupa G.N.

7 DATA AVAILABILITY STATEMENT

Data available upon request to authors.

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