Review

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Cocoa Bean Fermentation in Ivory Coast: Processes, Challenges, and Innovations for Uncompromising Market Quality

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Abstract

Ivory Coast accounts for approximately 40% of global cocoa production, with an annual average output of 2 million tons, consolidating its position as the world's leading producer. Over 6 million people—nearly one-quarter of the Ivorian population—depend directly or indirectly on this sector. The quality of cocoa beans, particularly their **degree of fermentation**, plays a decisive role in determining the competitiveness of Ivorian cocoa on an international market that is increasingly demanding in terms of sensory attributes, food safety, and environmental sustainability. Fermentation, which contributes 25 to 30% of the post-harvest added value, is a critical step that shapes the organoleptic properties (aroma, color, texture) of the final chocolate product. However, nearly 35% of exported beans exhibit defects related to incomplete or poorly managed fermentation, leading to economic losses estimated between 10% and 30% of the potential export value. These shortcomings are largely due to the heterogeneity of fermentation practices, inadequate equipment, limited knowledge of microbial dynamics, and insufficient incentives for quality enhancement. This article explores current trends in cocoa bean fermentation in Ivory Coast through five key dimensions: 1) scientific and microbiological foundations of the process; 2) traditional practices and their limitations; 3) market requirements and economic challenges; 4) emerging technological and organizational innovations; and 5) future prospects for standardization and traceability. The study underscores the urgent need for national quality standards and differentiated valorization mechanisms for well-fermented beans, which can command premium prices of up to US/$300 per ton. Strengthening the technical capacity of local stakeholders, modernizing fermentation infrastructure, and integrating research-based innovations are essential levers to ensure the high marketability of Ivorian cocoa.

Keywords: cacao bean fermentation; Ivory Coast; market quality

1. Introduction

Ivory Coast is the world's leading producer of cocoa beans, providing more than 40% of the global supply [1]. This product is a major source of income for millions of Ivorian farmers and a national economic pillar. However, the quality of fermented beans remains a key concern to ensure the competitiveness of Ivorian cocoa in international markets, where requirements for flavour, biochemical composition and safety continue to grow [2,3]. Fermentation is a decisive step in the development of chocolate flavour precursors, significantly influencing the organoleptic, physicochemical and microbiological properties of the beans [4,5]. This complex process, driven by natural microbial successions including yeasts, lactic acid bacteria and acetic acid bacteria, allows the hydrolysis of bitter compounds, the degradation of mucilage and the generation of volatile compounds characteristic of fermented cocoa [6–8]. In Ivory Coast, fermentation is mainly carried out by traditional, often empirical methods, using wooden crates, banana leaves or simply covered piles, which leads to a heterogeneity of quality [9] Faced with these challenges, improvement initiatives have emerged, including the use of starter cultures, the standardization of fermentation conditions (temperature, time, aeration), and the introduction of digital monitoring technologies [10,11]. These innovations aim to optimize fermentation to guarantee impeccable marketable quality, while meeting the challenges of sustainability, certification and traceability required by contemporary markets [12,13] In addition, socio-cultural, economic and climatic issues make it necessary to adapt local fermentation practices in order to ensure the resilience of the sector in the face of global challenges [14] This study aims to examine in depth the fermentation process of cocoa beans in Ivory Coast, to analyze the constraints and opportunities related to its control, and to highlight the innovations likely to guarantee its performance and quality. In addition, the growing pressure from consumers for sustainable, fair trade and traceable products requires a review of cocoa value chains, incorporating certification standards such as UTZ, the Rainforest Alliance or Fairtrade [15,16] These certifications encourage better control of post-harvest processes, including fermentation, by reinforcing good agricultural and post-harvest practices [17] At the same time, scientific research highlights the impact of agroecological conditions (climate, soil, variety) on fermentation dynamics and final bean quality, suggesting territorialized optimization approaches [18,19]. Notable efforts are also being made to raise awareness among producers' cooperatives of the importance of rigorous control of the fermentation process via simple and accessible analytical tools [20] In this respect, the integration of routine physicochemical analyses (pH, temperature, acidity, degree of fermentation) is a promising avenue for strengthening the professionalization of the sector [21].

2. Background and Importance of Fermentation in Ivory Coast

Ivory Coast, the world's largest producer of cocoa beans with more than 2 million tons per year [22], relies largely on the quality of its cocoa to maintain its position in the global chocolate market. The fermentation of the beans, which is an essential post-harvest step, plays a decisive role in the development of flavor precursors such as organic acids, volatile compounds and oxidized polyphenols, which give chocolate its sought-after sensory characteristics [23].

Traditionally carried out in the field by producers, this natural fermentation lasts between 5 and 7 days and is mainly based on artisanal processes, such as the use of banana leaves or wooden crates. However, studies have shown that this variability in practices leads to heterogeneity in the quality of the cocoa produced, which can negatively affect its commercial value [8,24]. Traditionally carried out in the field by producers, this natural fermentation lasts between 5 and 7 days and is mainly based on artisanal processes, such as the use of banana leaves or wooden crates. However, studies have shown that this variability in practices leads to heterogeneity in the quality of the cocoa produced, which can negatively affect its commercial value [8,24]. In this context, the improvement and control

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of the fermentation process represents a major challenge to strengthen the competitiveness of the Ivorian cocoa sector, while promoting sustainable, traceable production that respects international quality standards.

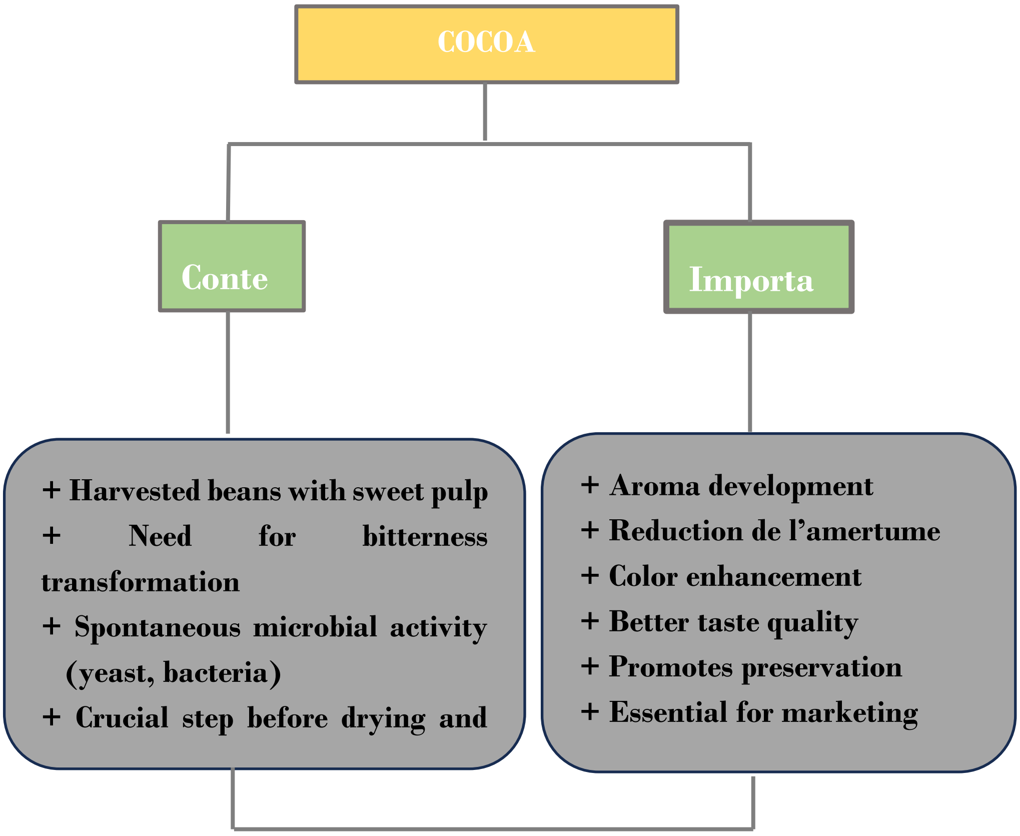

Figure 1. Background and importance of cocoa bean fermentation.

2.1. Cocoa in the Ivorian Economy

Ivory Coast remains the world's leading cocoa producer, with annual production exceeding 2 million tons, or nearly 40% of global supply. This global leadership has been consolidated over the decades thanks to favorable agroclimatic conditions, strong mobilization of smallholder producers, and continuous institutional support. The cocoa sector represents the main pillar of the Ivorian agricultural economy, contributing to about 15% of the gross domestic product (GDP), more than 40% of export earnings and providing direct or indirect employment to nearly 6 million people, or about a quarter of the national population **[25,26]**. Here is a simple but effective illustrative diagram showing the importance of cocoa in the Ivorian economy, structured in 5 poles:

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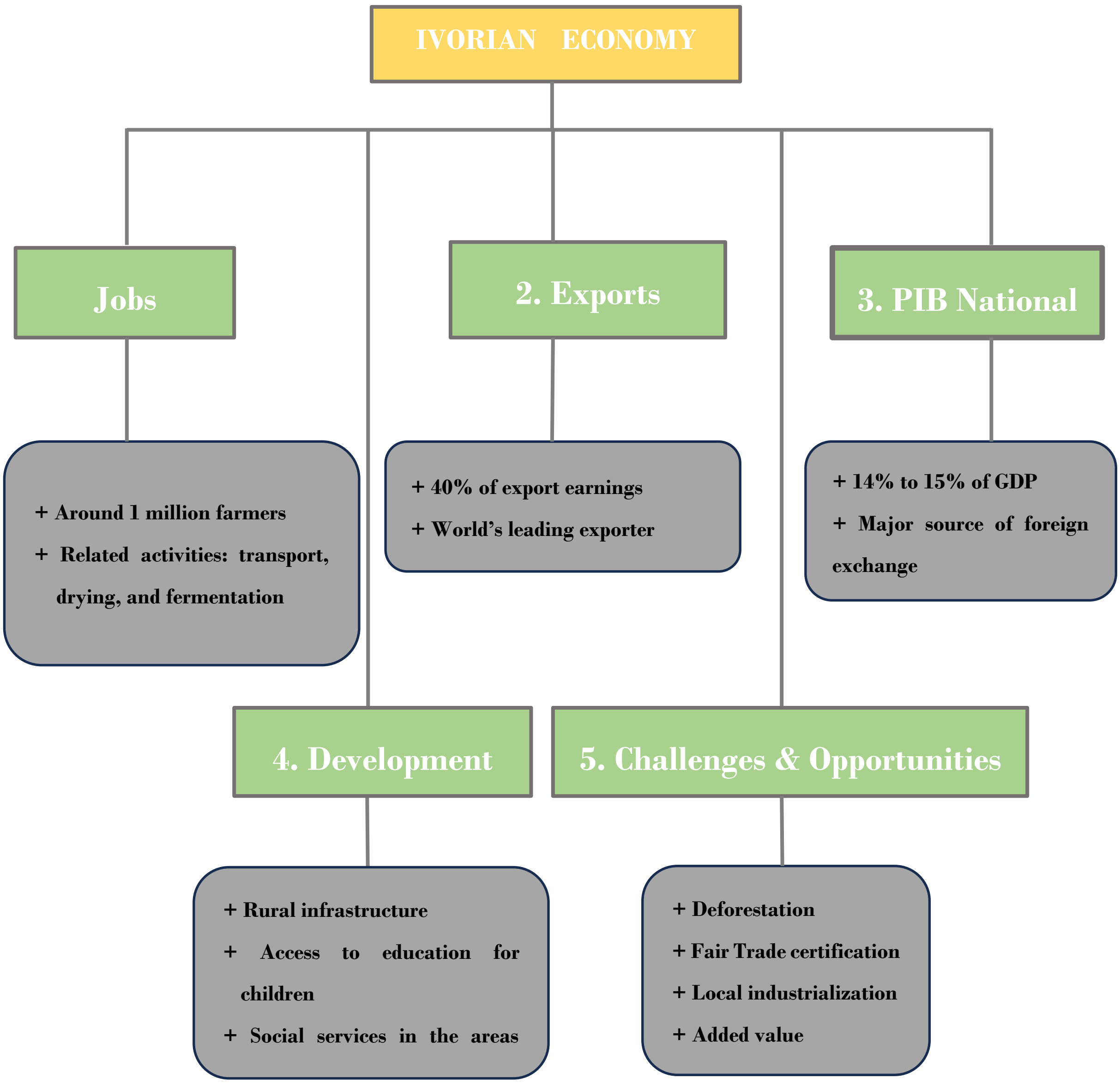

Figure 2. Importance of cocoa in the Ivorian economy.

This diagram highlights the crucial role of cocoa in the Ivorian economy structured in 5 poles: highlighting its weight in employment, exports and national GDP. It also shows the positive social impact on rural communities. Finally, it recalls the environmental challenges and opportunities for sustainable development linked to this sector.

This cash crop is not only an essential source of foreign exchange for the Ivorian State, but also a driver of rural development, ensuring the livelihood of more than 800,000 family farms [27]. However, despite its macroeconomic importance, the cocoa sector still faces many structural challenges. These include low producer incomes, dependence on international markets, price volatility, land degradation, deforestation and child labour [28,29]. On the commercial level, the growing requirements in terms of traceability, environmental sustainability and organoleptic quality of beans require a profound transformation of agricultural and post-harvest practices. Thus, the modernization of key stages of the value chain, in particular fermentation and drying, is now considered a strategic lever for improving the quality of Ivorian cocoa, increasing its added value and strengthening its competitiveness on international markets [30]. In addition, the integration of international standards (such as UTZ, Rainforest Alliance or Fairtrade) in production makes it possible to meet consumer expectations while promoting more sustainable and fair models for producers **[31,32]**.

2.2. Fermentation: A Qualitative Pivot for Post-Harvest Cocoa Quality

Fermentation is a decisive step in the post-harvest processing of cocoa beans (Theobroma cacao L.), conditioning their biochemical, sensory and commercial properties. It is used immediately after de-denting, and its role is twofold: to remove the mucilaginous pulp that surrounds the beans and to induce a series of biochemical transformations essential to the formation of the precursors of the aromas characteristic of chocolate (33). This spontaneous process is directed by a dynamic succession of microorganisms:

-Yeasts (*Saccharomyces cerevisiae, Hanseniaspora* spp.), lactic acid bacteria (*Lactobacillus* spp., *Leuconostoc* spp.) and acetic acid bacteria (*Acetobacter* spp.), then spore-forming bacteria (*Bacillus* spp.) which interact synergistically. Yeasts initiate fermentation by converting the sugars in the pulp into ethanol and CO_2.

-Then, lactic acid and acetic bacteria metabolize these compounds into organic acids (acetic, lactic), creating an acidic and thermal environment favorable to the destruction of the embryo and intra-bean enzymatic activation **[7,34,35]**.

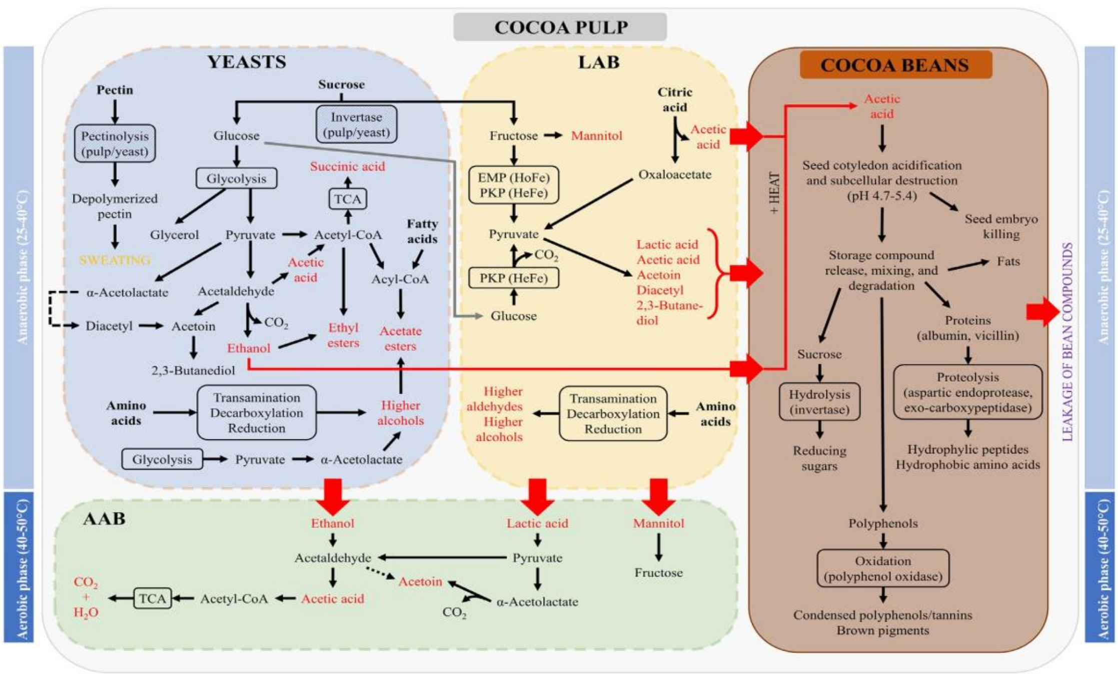

Figure 3. Fermentation of cocoa's pulp of starch mass [7] : Overview of the fermentation of the pulp of starch mass of cocoa through the succession of an anaerobic phase, involving yeasts and lactic acid bacteria (BAL), and an aerobic phase, involving acetic bacteria (BAA), as well as the concomitant bioconversion reactions occurring inside the cocoa beans. Substrate uptake and metabolite secretion by microbial cells are not shown. EMP : Embden-Meyerhof-Parnas Road; HeFe : heterofermentation; HoFe : homofermentation; PKP : phosphoketolase pathway; TCA : tricarboxylic acid cycle.

These transformations allow the production of precursors of volatile compounds such as aldehydes, superior alcohols and esters that directly influence the aromatic profile of cocoa **[18,36,37]**. The control of fermentation parameters (duration, temperature, aeration, turnaround rate, type of container used) is crucial. Fermentation that is too short or poorly conducted leads to incomplete aromatic development and the persistence of organoleptic defects such as astringency or bitterness **[38,39]**. Conversely, excessive fermentation can lead to high residual acidity and the degradation of aromatic compounds. In Ivory Coast, the world's leading cocoa producer, fermentation is still mainly carried out in an artisanal way, often in piles or in wooden crates. However, recent innovations include the use of thermoregulated modular tanks, perforated jute bags or biosensor-assisted controlled fermentation systems, with the aim of standardizing processes, improving aromatic yields and reducing post-harvest losses [40]. Conversely, excessive fermentation can lead to high residual acidity and the degradation of aromatic compounds. In Ivory Coast, the world's leading cocoa producer, fermentation is still mainly carried out in an artisanal way, often in piles or in wooden crates. However, recent innovations include the use of thermoregulated modular tanks, perforated jute bags or biosensor-assisted controlled fermentation systems, with the aim of standardizing processes, improving aromatic yields and reducing post-harvest losses **[41,42]**.

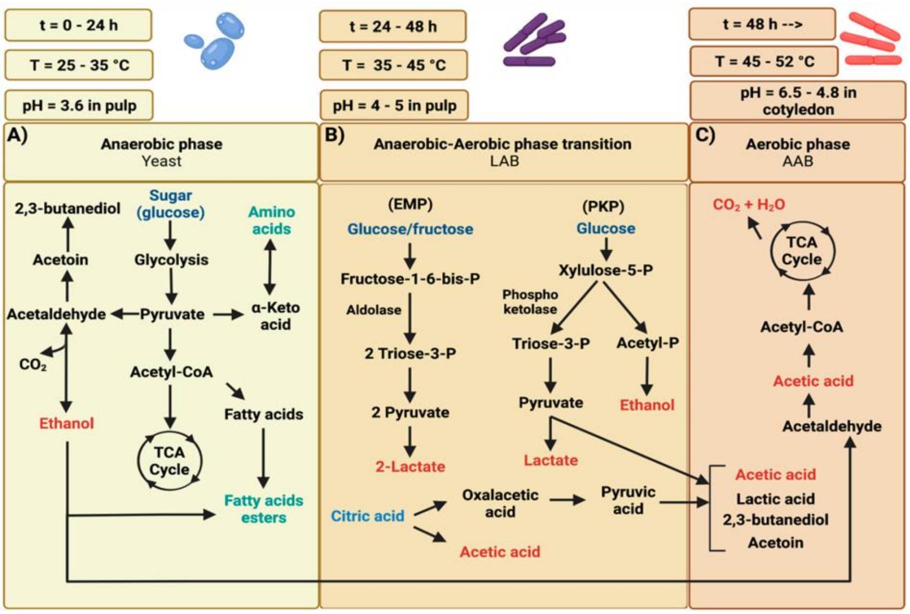

Figure 4. Main Phases of cocoa fermentation [2] : (A) Yeasts metabolize glucose (sugar) by the glycolytic pathway, transforming it into pyruvate. This process allows for the production of ATP and the regeneration of reduced coenzymes. The pyruvate is then converted to ethanol and carbon dioxide (CO_2), in an anaerobic environment. (B) Lactic acid bacteria (LABs) also use glucose, but in two distinct metabolic pathways: – The Embden-Meyerhof-Parnas (EMP) pathway in homofermentative LABs, resulting mainly in the production of lactic acid, – The phosphoketolase (PKP) pathway in heterofermentative LABs, which leads to the formation of lactic acid, ethanol (or acetic acid) and CO_2. (C) Finally, acetic acid bacteria (AABs) intervene by oxidizing the ethanol produced by yeasts. This process, under aerobic conditions, results in the formation of acetic acid, a key compound in the acidification of the fermentation environment, [2] .

3. The Fermentation Process of Cocoa Beans

3.1. Biochemical and Microbial Process

The fermentation of cocoa beans is an essential post-harvest process, not only for the removal of the mucilaginous pulp surrounding the beans, but above all for the development of the characteristic aroma precursors of chocolate. It is a spontaneous, i.e., non-inoculated, fermentation triggered by the microbial flora naturally present on the pods, agricultural tools, cover sheets (often banana leaves) and in the fermentation environment *[7,33,39,43]*. This fermentation takes place in three successive microbiological phases over a typical period of 5 to 7 days (although some industrial practices experiment with optimized durations). These phases are characterized by specific microbial dynamics that interact closely with the physicochemical factors of the environment, including temperature, pH, oxygen content, and available substrates *[18,44]*.

3.1.1. The Different Phases

Phase 1: Yeast colonization

Yeasts, mainly *Saccharomyces cerevisiae, Hanseniaspora opuntiae, Pichia kudriavzevii and Candida tropicalis,* dominate the initial fermentation phase. They use the simple sugars (glucose, fructose, sucrose) in the pulp to produce ethanol, carbon dioxide (CO_2), and volatile organic compounds such as acetaldehyde, methanol, and fruity esters [45,46] This activity causes a partial degradation of the pulp and a decrease in the redox potential, promoting the growth of lactic acid bacteria, (Eq. 1).

$$\text{Glucose } (C_6H_{12}O_6) \xrightarrow{\text{Yeasts}} 2 \text{ Ethanol } (C_2H_5OH) + 2CO_2 + \text{Energy (ATP)}$$

Phase 2 : Development of lactic acid bacteria (LAB)

Lactic acid bacteria, including *Lactiplantibacillus plantarum* (formerly *Lactobacillus plantarum), Leuconostoc mesenteroide*s and *Weissella cibaria*, proliferate in a still relatively anaerobic environment. They metabolize sugars and ethanol into lactic acid, reducing the pH of the medium to values close to 4.0–4.5. This partial acidification initiates intracellular stress in the beans, which contributes to the progressive death of the embryo [21],(Eq. 2)

$$\text{Ethanol } (C_2H_5OH) + O_2 \xrightarrow{\text{Acetic bacteria}} \text{Acetic acid } (C_3COOH) + H_2O + \text{Heat}$$

Phase 3: Acetic Acid Bacteria Growth (AAB)

As the pulp is degraded, the environment becomes more and more aerated, allowing the development of aerobic acetic bacteria such as *Acetobacter pasteurianus* and *Gluconobacter oxydans*. These bacteria oxidize ethanol into acetic acid, generating heat and inducing a temperature rise of up to 45 to 50 °C. Acetic acid diffuses into the beans, contributing to their internal acidification and causing cell lysis [47,48]. This heat and acid stress triggers the release of endogenous enzymes (proteases, glucosidases), which are responsible for the degradation of proteins into peptides and amino acids, and complex carbohydrates into simple sugars. All these compounds act as aroma precursors during roasting [38,49] (Eq. 3).

$$\text{Glucose } (C_6H_{12}O_6) \xrightarrow{\text{lactic bateria}} \text{Lactic acid } (C_3H_6O_3) + \text{Energy (ATP)}$$

3.1.2. Chemical Reactions and Physical Transformations

At the same time, enzymatic reactions such as the oxidation of polyphenols by polyphenol oxidases (tyrosinase, laccase) lead to browning of the beans and the formation of pigments (theaflavins, thearubigins). These reactions affect the internal color, texture, and future aromatic complexity of the cacao [50]. Poor process management such as insufficient aeration, inadequate fermentation time, or overheating can disrupt this microbial and enzymatic succession. This leads to the production of lower quality beans, with sensory defects (excessive acidity, unbalanced aromas, residual bitterness) or storage problems [51]

3.2. Traditional Fermentation Techniques in Ivory Coast

Ivory Coast, the world's leading cocoa producer, accounts for nearly 40% of the world's production. Post-harvest fermentation is a crucial step in the development of cocoa's aroma precursors. Despite technological advances, the majority of Ivorian producers continue to use traditional fermentation methods, transmitted empirically. These methods are strongly influenced by local practices, the level of organization of producers, the availability of infrastructure and the volumes processed. The three most commonly used methods are: heap fermentation, wooden crate fermentation (or tanks), and pit fermentation. Each of these techniques has advantages and limitations that influence the fermentation kinetics, the microbial profile, and ultimately, the quality of the beans.

3.2.1. Heap Fermentation

Heap fermentation (Figure 5) is the most accessible method for small producers due to its simplicity and low cost. It consists of piling the cocoa beans on banana leaves or directly on the ground, then covering them with leaves to limit heat loss and promote constant humidity. However, the lack of control over key parameters — temperature, aeration, drainage — can lead to

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inhomogeneous fermentations and microbiological imbalances, negatively affecting the organoleptic characteristics of cocoa [52].

(**a**) (**b**)

Figure 5. Fermentation of cocoa beans in heaps according Ivorian's methods : (**a).** Heap fermentation of cocoa beans on banana leaves under field conditions, illustrating the initiation of spontaneous microbial succession and heat build-up. (**b**). Cocoa bean mass covered with banana leaves, highlighting the maintenance of humidity, restricted aeration, and favorable conditions for lactic acid and acetic acid bacterial activity.

In addition, the use of banana leaves, although abundant and biodegradable, has several limitations. Their rapid decomposition under the combined effect of heat and humidity can generate undesirable compounds, create an excessive anaerobic environment or serve as a vector for contaminating microorganisms [53,54]. This degradation can also compromise the homogeneous coverage of the beans, affecting the diffusion of heat and oxygen, necessary for efficient fermentation. From an environmental point of view, the systematic harvesting of banana leaves for fermentation operations can disturb the balance of banana plantations by reducing the biomass available in the soil, which limits organic restitution and increases soil erosion. In addition, this practice can disturb the microhabitats of insects, fungi and other organisms associated with fallen leaves, thus altering local biodiversity. Finally, when abandoned en masse after use, decaying leaves can emit greenhouse gases such as methane, especially in prolonged anaerobic conditions.

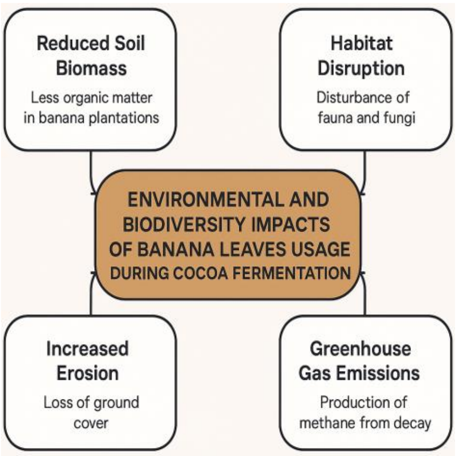

Figure 6. Limitations of fermentation of cocoa beans on banana leaves.

3.2.2. Fermentation in Wooden Crates (Bins)

The method of wooden crates, usually made of untreated and perforated wood, is increasingly encouraged in organized cooperatives or as part of certification schemes, (Figure 7). It allows for better temperature control (45–50 °C), good aeration and efficient evacuation of the exuded liquid, called “sweatings” [55]. In addition, the periodic turning of the beans (every two days or so) promotes a homogeneous distribution of microorganisms (yeasts, lactic acid and acetic acid bacteria), which is essential for the development of aroma precursors such as aldehydes and volatile acids [56].

(**a**) (**b**)

Figure 7. Illustrates the setup of the wooden crates and highlights the interactions between microbial activity and the fermentation environment. Fermentation in wooden crates: (a) **Microbial Activity**: The wooden crates provide a natural environment that supports the growth and activity of beneficial microorganisms. This activity drives the breakdown of substrates, leading to the production of desired metabolites such as acids, flavors, and aromas. (**b)** Physical and Chemical Environment: The wooden crates influence moisture retention, aeration, and temperature regulation during fermentation. These conditions help maintain an optimal environment for microbial development, ensuring uniform fermentation and improved product quality.

3.2.3. Fermentation in Pits

Still used in some isolated rural areas, pit fermentation consists of burying the beans in holes covered with plastic sheeting or leaves. Although this method conserves the heat generated by fermentation, it has several major drawbacks: High risk of faecal or fungal contamination, poor evacuation of liquids, poor aeration and difficulty in turning [57]. These conditions impair optimal microbiological development, resulting in incomplete or unbalanced fermentation.

3.2.4. Other fermentation Techniques Using Emerging Media

Banana leaves with the best attributes are becoming increasingly difficult to find in the main cocoa production areas and are now a limiting factor in this main post-harvest process. In addition, the use of banana leaves considerably reduces banana production and leads to the scarcity and high cost of plantains. In order to address the shortage of banana, leaves caused by various factors, smallholder farmers, who are responsible for the largest volumes of cocoa production in the main cocoa growing areas of Ivory Coast, are resorting to new emerging carriers such as palm leaves, polypropylene tarpaulin, cocoa pod, polypropylene bag and jute bag in addition to traditional carriers such as banana leaves, Black plastic sheeting (Figure 8) [58]. These modern cocoa fermentation techniques aim to improve the control of physicochemical conditions such as temperature, aeration and humidity, which are critical factors for the optimal development of fermentative microorganisms [19,36. They also reduce the risk of contamination by undesirable microorganisms, thus promoting more hygienic and controlled fermentation [55]. As a result, these methods help to increase the organoleptic quality and consistency of the final product, compared to traditional fermentations in piles or wooden boxes, which are more exposed to environmental variations and contamination [56,57]. In addition, the use of polyester, tarpaulin or vinyl tanks offers a more stable fermentation environment, facilitating industrial control and standardization of processes [54].

Figure 8. Different fermentation supports are emerging in Ivory Coast: (**a**) Palm leaves, illustrating a traditional alternative with limited aeration control; (**b**) Cocoa pod, a rudimentary method conserving heat but restricting microbial dynamics; (**c**) Polypropylene tarpaulins, improving drainage and partial control of fermentation conditions; (**d**) Polypropylene bags, offering low-cost containment but with risks of anaerobiosis and overheating; (**e**) Jute bags, enhancing aeration compared to synthetic bags and supporting microbial succession; and (**f**) Polyester tanks, enabling improved temperature regulation, aeration, and process standardization.

3.2.5. Turning of Beans, Importance and Consequences

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- Importance of reversal

Regardless of the method used, turning the beans is a key practice for successful fermentation. This procedure, generally carried out from the 2nd day, ensures better oxygenation of the beans, stimulates the metabolism of acetic bacteria, and allows the conversion of ethanol (produced by yeasts) into acetic acid. This exothermic reaction is essential for increasing the internal temperature of the ferment, often between 45 and 50 °C, and for activating the endogenous enzymes responsible for the formation of aromas [49,62]

- *Consequences on bean quality*

The final quality of cocoa depends closely on the fermentation conditions. A well-conducted fermentation allows the development of complex aromatic profiles (floral, fruity, roasted notes) and a homogeneous brown coloring of the cotyledon, fundamental criteria for commercial classification. Conversely, incomplete fermentation can lead to excessive residual acidity, an earthy or musty taste, and rejection by international buyers [63].

3.3. Factors Influencing Process Efficiency

The efficiency of the cocoa bean fermentation process depends on many physicochemical, biological and technological factors. These factors interact in complex ways to determine the final quality of fermented beans, influencing aroma development, bitterness reduction and embryo death. The main factors include the variety of cocoa, the thickness of the fermented mass, the ambient temperature, the frequency of turning, the fermentation time, as well as the microbiota present.

3.3.1. Variety of Cocoa

The genetic variety of the pods influences the biochemical composition of the beans (sugar, organic acid, polyphenol content, etc.), which modifies the kinetics of microbial fermentation. For example, Forastero-type beans have a more abundant pulp, favoring rapid fermentation, while Criollo or Trinitario varieties may require more controlled conditions to reveal their fine aromas [17,64]

3.3.2. Thickness of the Fermented Mass

The height or thickness of the bean mass (often measured in centimeters or number of layers) influences thermal development and oxygen distribution. A mass that is too thick (>60 cm) can generate anaerobic zones or overheating that disrupt microbial metabolism and alter the quality of the product [55] Masses between 40 and 60 cm are generally recommended to ensure homogeneous fermentation.

3.3.3. Ambient Temperature

Temperature plays a decisive role in enzymatic activation and microbial development. Fermentation ideally takes place at a temperature of between 40 and 50 °C. Below this threshold, microbial activity is slowed down; above 50 °C, beneficial yeasts and bacteria are inhibited or even destroyed [33]. Temperature is partly regulated by exothermic microbial activity and by local climatic conditions.

3.3.4. Rollover Frequency

Stirring or turning the beans allows for better aeration and homogeneity of the process. It promotes the development of acetic acid bacteria that convert ethanol into acetic acid, which is essential for the destruction of cotyledons and the formation of aroma precursors [33] A two-day rollover frequency is generally considered optimal in traditional systems.

3.3.5. Total Fermentation Time

The duration of the process varies depending on the variety of cocoa and the fermentation system used. It generally lasts from 5 to 7 days for Forastero beans, and up to 8 days for Criollo beans [47]. Fermentation that is too short compromises embryonic death and aroma generation, while excessive fermentation can lead to dry matter losses, mould or excessive acidity.

3.3.6. Microbiota and Sanitary Conditions

The initial microbial diversity, influenced by the material, the environment, and the cultural practices, determines the sequence of alcoholic, lactic and acetic fermentations. Bacteria such as Lactobacillus spp., Acetobacter spp., and yeasts of the genus Saccharomyces or Hanseniaspora are essential for efficient fermentation [37,41]. The hygiene of the equipment (containers, banana leaves, etc.) also impacts the quality of the microbiological profile. Optimal fermentation therefore relies on the concerted control of these factors, which must be adapted to the specifics of the raw material and the local conditions. Improving traditional practices through a better understanding of microbial and environmental parameters paves the way for a qualitative standardization of cocoa beans.

3.4. Important Roles of Yeasts During Cocoa Bean Fermentation, Environment, Diversity and Aroma Production

Fresh cocoa pulp provides a favourable environment for yeast growth, due to its physicochemical characteristics: anaerobic environment, high content of fermentable sugars and relatively low pH, which limits the growth of many other microorganisms [4]. Numerous studies have highlighted a significant diversity of yeasts involved in the fermentation of beans. The most frequently identified genera are *Pichia*, *Saccharomyces cerevisiae*, *Hanseniaspora* and *Candida*. Other, less abundant genera include *Wickerhamomyces*, *Torulaspora*, *Kluyveromyces*, and *Rhodotorula* [10,12,14,35,46,65,66]. Concerning the most recurrent species during the fermentation process, several authors agree to mention, in order of decreasing frequency: *Saccharomyces cerevisiae*, *Pichia kudriavzevii*, *Hanseniaspora opuntiae*, *Hanseniaspora uvarum*, *Hanseniaspora guilliermondii*, *Pichia manshurica*, *Pichia kluyveri* and *Candida tropicalis*. The main metabolic functions of yeasts during cocoa fermentation include the production of volatile organic compounds (VOCs), the hydrolysis of pectin, as well as the fermentation of carbohydrates [67]. In addition, some species have notable antifungal properties [38,68] and the ability to metabolize citric acid [69]

Table 1. Role of leaveners on the organoleptic quality of derived products, (Aldehydes and ketones).

Yeasts	VOC	Sensory Descriptor	References
Aldehydes and ketones			
S. cerevisiae	Acetaldehyde	Green apple	[7][1]
C. metapsilosis	Benzene acetaldehyde	Green	[70][1]
S. cerevisiae, K. marxianus, P. kudriavzevii	Phenylacetaldehyde	Floral, honey	[11,71,72][1]
S. cerevisiae	2-butanal	Fruity, grassy	[7][1]
S. cerevisiae	2-hexanal	Fruity, grassy	[7][1]
S. cerevisiae, C. metapsilosis, Galactomyces geotrichum, P. pastoris; S. carlsbergensi, P. kudriavzevii	Benzaldehyde	Almond, hazelnut, candy, burnt sugar	[16,70,71,73][1]
S. cerevisiae	Butanal, 2-methyl-	Malty, chocolate	[74,75][1]
S. cerevisiae, C. metapsilosis	Butanal, 3-methyl-	Malty, chocolate	[70][1]
S. cerevisiae	2-Methylpropanal	malty/nutty/chocolate	[7][1]
S. cerevisiae, P. kudriavzevii	2-Phenylbut-2-enal	Floral, honey, powdery, cocoa	[71][1]

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S. cerevisiae, P. kudriavzevii	5-Methyl-2-phenyl-2-hexenal	Cocoa	[71] [1]
S. cerevisiae, P. kudriavzevii	Acetophenone	Floral, fruity, almond, pungent, sweet	[70,71,74] [1]
S. cerevisiae	2-heptanone	Floral, fruity	[7]
P. kudriavzevii	2-nonanone	Fruity, sweet, waxy, green herbaceous	[71]

[1] The numbers in parentheses represent the different scientific authors.

Table 2. Role of leaveners on the organoleptic quality of derived products, (Alcohols).

Yeasts	VOC	Sensory Descriptor	References
	Alcohols		
S. cerevisiae	Glycerol	Sweet	[70,74] [1]
S. cerevisiae	2,3-butanediol	Fruity, creamy, buttery	[70,74] [1]
S. cerevisiae	2-Propyldecan-1-ol	Floral	[70] [1]
S. cerevisiae	Benzene ethanol	Floral	[70] [1]
S. cerevisiae	1-butanol–3 methyl	Fruity, malty, bitter, chocolate	[70,74] [1]
S. cerevisiae, C. tropicalis, G. geotrichum,	2-phenylethanol	Fruity, floral, honey, rummy	[11,19,71,73,74,76,77] [1]
H. guilliermondii, H. uvarum, K. lactis, K. marxianus,	2-heptanol	Fruity, floral, citrus, herbal	[11,71,72] [1]
P. anomala, P. farinosa, P. kudriavzevii, W. anomalus,	2-nonanol	Fat, green	[71] [1]

[1] The numbers in parentheses represent the different scientific authors.

Table 3. Role of leaveners on the organoleptic quality of derived products, (Acids).

Yeasts	VOC	Sensory Descriptor	References
	Acids		
S. cerevisiae	Acetic acid	Sour, vinegar	[71] [1]
C. metapsilosis	Butanoic acid	Chessy	[70] [1]
S. cerevisiae	2-methylbutanoic acid	Sweaty	[7] [1]
S. cerevisiae	3-methylbutanoic acid	Sweaty, rancid	[70,72] [1]
P. kudriavzevii	Octanoic acid	Sweat, fatty	[71] [1]

[1] The numbers in parentheses represent the different scientific authors.

Table 4. Role of leaveners on the organoleptic quality of derived products, (Esters).

Yeasts	VOC	Sensory Descriptor	References
	Esters		
S. cerevisiae, C. tropicalis, C. utilis, H. guilliermondii, H. uvarum, K. apiculate, P. anomala, P. farinosa, P. kudriavzevii, W. anomalus, K. lactis	Ethyl acetate	Floral	[19,73,75,78] [1]

S. cerevisiae	Acetic acid, ethyl ester	Fruity, sweet	[70][1]
P. kudriavzevii	Benzyl acetate	Floral, jasmine	[71][1]
S. cerevisiae	Ethyl octanoate	Fruity, floral	[70][1]
S. cerevisiae, P. kudriavzevii	Isoamyl benzoate	Balsam, sweet	[71][1]
P. kudriavzevii	Ethyl dodecanoate	Sweet, floral	[71][1]
S. cerevisiae, C. metapsilosis	Ethylphenyl acetate	Floral	[71][1]
S. cerevisiae, H. guilliermondii, H. uvarum,K. marxianus, P. anomala, P. farinosa, P. kudriavzevii	2-Phenylethyl acetate	Fruity, sweet, roses honey, floral	[71][1]

[1] The numbers in parentheses represent the different scientific authors.

Table 5. Role of leaveners on the organoleptic quality of derived products, (Others compounds).

Yeasts	VOC	Sensory Descriptor	References
Others			
S. cerevisiae	2-acethyl-1-pyrrole	Caramel/chocolate/roasty	[7][1]
C. metapsilosis	2-Phenylethyl formate	Floral	[70][1]
S. cerevisiae, P. kudriavzevii	Tetramethylpyrazine	Roasted cocoa, chocolate	[71][1]
S. cerevisiae	Linalool	Floral	[71][1]

[1] The numbers in parentheses represent the different scientific author.

4. Issues Related to the Marketability of Ivorian Cocoa

4.1. International Quality Standards

The marketability of cocoa is a key determinant of its competitiveness on international markets. Importing countries, particularly in Europe, North America and Asia, impose rigorous standards that govern the physical, chemical, organoleptic and health quality of cocoa beans. The requirements focus on the following criteria :

- Complete fermentation (between 5 and 7 days), essential for the development of aroma precursors and the reduction of bitterness and astringency of the beans [75];
- A humidity level ≤ 7 % to avoid fungal growth and the risk of contamination by mycotoxins (in particular ochratoxin A) [76];
- The absence of chemical contaminants (pesticide residues, heavy metals), biological contaminants (mosses, moulds, insect fragments) or physical contaminants (foreign bodies, defective beans) (Codex Alimentarius, 2021; ISO 2451:2021);
- Good uniformity of the beans in terms of size, appearance (absence of flat, sprouted or moldy beans), and fermentation visible on the test cut ;
- The traceability of the product, required by sustainability standards, which make it possible to guarantee verified origin, responsible agricultural practices and respect for social and environmental rights [77].

The European Union, with the implementation of Regulation (EU) 2023/1115 on deforestation-free products, now requires that imported beans are not only traceable but also free of origin linked to deforestation or forest degradation. This increases the pressure on producing countries such as Ivory Coast, the world's largest producer, to implement reliable geolocated traceability systems [82]

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Thus, sustainable access to international markets depends on the ability of Ivorian producers to meet the combined requirements of physical quality and socio-environmental compliance. The adoption of good post-harvest practices (controlled fermentation, hygienic drying, adequate storage) and certification systems is a strategic lever to maintain the competitiveness of Ivorian cocoa in a changing global market.

4.2. Constraints Encountered by Producers

Despite the numerous training and extension initiatives implemented by the Ivorian government and technical partners, cocoa producers continue to face several major constraints that affect the marketability of cocoa.

- Firstly, the lack of suitable equipment for the post-harvest stages, in particular fermentation and drying, remains a major obstacle. In many cocoa-growing areas, producers still use rudimentary devices such as poorly designed fermentation pits or plastic sheeting on the ground for drying, which compromises the optimal development of aromas and promotes the appearance of mould or purple beans [30].

Secondly, a persistent lack of knowledge of the role of the microorganisms involved in the fermentation process is an important limitation. Fermentations are often carried out empirically, without control of parameters such as temperature, aeration or duration, which leads to incomplete or heterogeneous fermentations. However, it is now established that microbial dynamics, in particular the coordinated activity of yeasts, lactic acid and acetic acid bacteria, are decisive for the production of high-quality cocoa *[17,35]*

- Third, the pressure of the agricultural calendar and the need to harvest quickly before rains or flight often lead to shortcuts in post-harvest practices. Fermentation is sometimes shortened, or the beans are dried inappropriately, which affects the uniformity of the physicochemical quality of the finished product [83] This factor is aggravated by the absence of a strong collective organization in some areas, preventing the pooling of infrastructure and the synchronization of harvests.

In addition, socio-economic constraints such as the low level of education of some farmers, limited access to agricultural credit, or the low differentiated valuation of quality cocoa in current commercial channels, discourage the adoption of good practices [84] Indeed, even when producers adopt improved processes, they do not always benefit from a significantly higher selling price, which limits the economic incentive to maintain high quality standards. Finally, the impacts of climate change, in particular erratic rainfall and rising temperatures, indirectly influence cocoa quality through changes in fermentation and drying conditions, as well as in bean metabolism [85] In short, the constraints encountered by cocoa producers in Ivory Coast are the result of a set of technical, economic, organizational and climatic factors, which must be addressed in an integrated manner to ensure a sustainable improvement in the marketable quality of Ivorian cocoa.

4.3. Economic Impact

The post-harvest quality of cocoa, in particular the degree of fermentation of the beans, is a major determinant of its market value on international markets. Well-fermented cocoa with a uniform brown color, a developed aroma and a low proportion of purple or mouldy beans is generally valued by buyers and can be eligible for a quality premium of up to USD 300 to USD 500 per ton depending on the year and the market situation [86,87]. In Ivory Coast, the world's leading cocoa producer, poor mastery of traditional fermentation techniques can lead to organoleptic and physico-chemical defects that result in significant discounts ranging from USD 150 to USD 300/tons [22,26]. These economic losses directly impact the incomes of smallholder producers, who account for more than 90% of farmers, and weaken their ability to invest in better agricultural practices. The poor quality of beans undermines the competitiveness of Ivorian cocoa in specialty markets, particularly that of "bean-to-bar" chocolate, where processors require increased traceability and impeccable sensory quality [88].

This situation is a barrier to access to premium markets, despite the potential of some local varieties when they are well processed. Finally, the accumulation of poorly fermented beans in commercial channels accentuates the variability of quality at the national level, which can damage the overall reputation of Ivorian cocoa, which already faces challenges related to sustainability and child labor [89]. Improving the quality of fermentation therefore appears to be a strategic lever to increase added value at the local level and strengthen the competitiveness of the cocoa sector in a context of structural transformation of the Ivorian economy.

5. Technological Innovations and Improved Practices

5.1. Deployment of Innovative Technological Tools

The emergence of cutting-edge technologies in agri-food value chains offers major opportunities to improve the productivity, traceability, quality and sustainability of post-harvest systems, especially in the Global South. The integration of the Internet of Things (IoT), artificial intelligence (AI), robotics, as well as mobile technologies and renewable energy is profoundly transforming agricultural and post-harvest practices *[90,91]* In post-harvest operations, smart sensors integrated with IoT systems allow real-time monitoring of critical parameters such as temperature, relative humidity, gas concentration (ethylene, CO_2), or microbial activity. This significantly improves quality control during sensitive steps such as fermentation, drying, storage or transport [88]. For example, in the cocoa sector, these tools make it possible to dynamically adjust fermentation conditions to maximize aromatic profiles and reduce quality losses [64]. Drones and computer vision technologies are also used to map plots, detect areas at risk (presence of mold or fungal degradation), and monitor harvests in real time. Combined with digital platforms, these technologies facilitate fast, data-driven decision-making, even in remote rural areas [89]. Hybrid solar drying systems, combining solar energy and biomass, are a key innovation to improve the quality of drying while reducing dependence on non-renewable energy sources. These systems allow for more homogeneous, faster and better controlled drying, thus reducing the risk of microbiological contamination and mycotoxin development, while ensuring better nutrient retention [90,91]. In addition, the development of modular and transportable food processing modules, adapted to different production capacities, strengthens the technological autonomy of small rural enterprises. These mobile units, combined with tools for digitizing production data (traceability, certification, quality control), make it possible to move processed products upmarket for local, regional or international markets [92].

Finally, access to these technologies is facilitated by the development of mobile applications adapted to the African context, allowing producers and processors to obtain information on good processing practices, market prices, weather forecasts, and health alerts [97] These tools promote digital inclusion and the empowerment of smallholder producers, while boosting the competitiveness of agri-food value chains.

5.2. Integration of Digital Technologies for Quality Control and Traceability

Strengthening the capacities of agri-food cooperatives is a strategic lever for the sustainable improvement of the processing of agricultural products in rural and peri-urban areas. International technical cooperation programmes such as those carried out by CIRAD, GIZ, FAO or the EU-AU Food Systems programme contribute significantly to the empowerment of cooperatives through continuing education, advisory support and organisational structuring [98] These interventions are based on participatory approaches that promote the transfer of skills adapted to the local context, while encouraging social and technical innovation [95]. The pooling of processing equipment (shredders, solar dryers, pasteurization units, bagging machines) within cooperatives makes it possible to lower fixed costs, improve productivity and facilitate access to formal markets while respecting health requirements *[100,101]* This sharing economy logic also strengthens the logistical and organizational capacities of producers, thus promoting the emergence of territorialized value chains. In addition, action-training schemes, rooted in local socio-technical realities, have

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demonstrated their effectiveness in disseminating good practices in hygiene, artisanal processing, post-harvest conservation and quality management [98]. The introduction of simple digital tools (mobile applications for batch tracking, e-learning modules adapted to local languages) complements these systems and improves traceability and knowledge capitalization. In a context of agroecological transition and inclusive development, these cooperative dynamics not only strengthen the resilience of local food systems, but also contribute to the reduction of rural poverty, in particular by promoting the employment of young people and women [99].

5.3. Strengthening Scientific Research on Fermentation Flora and Starter Cultures

Support for national research centers (CNRA, Universities, Microbiology Laboratories) is essential to characterize the microbial diversity involved in traditional fermentation in Ivory Coast. Several recent studies have highlighted the importance of yeasts (*Saccharomyces cerevisiae*, *Hanseniaspora* spp.), lactic acid (*Lactobacillus* spp.) and acetic acid (Acetobacter spp.) bacteria in the development of aromas and the reduction of undesirable compounds [43,111]. The development of specific starter cultures adapted to local conditions would standardize the process while maintaining regional aromatic specificities. In addition, the design of prototypes of thermo-insulated and aerated fermentation crates or tanks, based on scientific results, would make it possible to optimize fermentation while meeting the economic constraints of small producers.

6. Conclusions

Ivory Coast, the world's leading cocoa producer, is facing a major strategic challenge: to improve the quality of its beans to meet the growing demands of the international market, both in terms of sensory, health and the environment. Fermentation, which accounts for up to 30% of post-harvest added value, remains a decisive step but is still insufficiently controlled. Defects linked to incomplete or poorly managed fermentation concern nearly 35% of the beans exported, causing considerable economic losses. This situation is mainly the result of a heterogeneity of practices, a lack of suitable equipment, a poor understanding of microbial processes and a valorization system that does not provide much incentive for quality. To meet these challenges and guarantee the irreproachable marketability of Ivorian cocoa, several levers of action are necessary :

-Develop a national fermentation reference system, based on standardized protocols and adapted to local agroecological contexts, in order to guarantee a constant and traceable quality of the beans.

-Develop and apply fermentative bio-inoculants from selected autochthonous microbial strains, to improve the efficiency and reproducibility of the fermentation process.

-Promote the dissemination of appropriate technologies, including simple, durable and accessible equipment to control critical fermentation parameters (temperature, drainage, aeration).

-Strengthen the capacities of local actors, by integrating continuous training on the microbiological, technological and economic aspects of fermentation.

-Encourage the creation of certified premium sectors, with a differentiated valuation of well-fermented beans, likely to generate quality premiums of up to USD 300/ton.

-Promote an integrated and partnership-based approach, by mobilizing researchers, cooperatives, public institutions and private sector actors to build effective governance of cocoa quality.

Thus, the modernization of the fermentation process, backed by a better valorization of quality beans, is a priority way to increase producers' incomes, strengthen the competitiveness of Ivorian cocoa and guarantee its sustainability on international markets..

7. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

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Data Availability Statement: Informed consent was not required for this study, as it did not involve human participants, animal experimentation, or the use of living organisms subject to ethical approval. The research focused exclusively on post-harvest processes, technological practices, and literature-based analyses related to cocoa bean fermentation in Côte d'Ivoire. No personal data, sensitive information, or identifiable materials were collected or processed during the course of this work.

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Abbreviations

The following abbreviations are used in this manuscript:

AA. : Aide acetic
B. : Bifidobacterium
C. : Candida
DF : Dietary fiber
EFSA : The European Food Safety Authority EPS Exopolysaccharide
EU : European Union
FAO : Food and Agriculture Organization IDF Insoluble dietary fiber
H. : Hanseniaspora
K. : Kluyveromyces
L. : Lactobacillus, Lacticaseibacillus, Lactiplantibacillus, Limosilactobacillus, and Levilactobacillus
LAB : Lactic acid bacteria
Lac. : Lactococcus
Leuc. : Leuconostoc
MRSA : Methicillin-resistant Staphylococcus aureus MW Molecular weight
P. Pichia
QPS Qualified Presumption of Safety
QSI : Quorum sensing inhibition
SCFA : Short chain fatty acids
SDF : Soluble dietary fiber
Str. : Streptococcus
S. Saccharomyces
T. : Torulaspora
UREM : Research and Teaching Unit in Microbiology

USA : United State of America
VOC : Volatile olfatic compounds
W. :Wickerhamomyces
WHO: World Health Organization

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