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Original Article

Amazonian fermentations: an analysis of industrial and social technology as tools for the development of bioeconomy in the region

Fermentações amazônicas: uma análise da tecnologia industrial e social como ferramentas para o desenvolvimento da bioeconomia na região

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Abstract

This review article explores the potential of fermentations in the Amazon region as catalysts for economic and social development. It highlights the rich cultural and gastronomic diversity of the Amazon, focusing on indigenous fermented products. Two main products, tucupi and caxiri, are discussed in detail, emphasizing their significance in local cuisine and culture. The review examines the challenges and opportunities for industrial applications of these products, as well as their potential for social technology initiatives, particularly in the context of family farming. The sustainable production of native fermented products in the Amazon is seen as a means to preserve biodiversity, empower local communities, and promote cultural heritage. The article concludes that both industrial and social technologies have complementary roles in promoting economic growth, cultural preservation, and the well-being of the Amazon region, making it a promising hub for innovative and sustainable fermented food products on a global scale.

Keywords: Amazon, fermentations, industrial technology, social technology, bioeconomy.

Resumo

Este artigo de revisão explora o potencial das fermentações na região amazônica como catalisadoras para o desenvolvimento econômico e social. Destaca a rica diversidade cultural e gastronômica da Amazônia, com foco nos produtos fermentados indígenas. Dois produtos principais, o tucupi e o caxiri, são discutidos detalhadamente, enfatizando sua importância na culinária e na cultura local. A revisão examina os desafios e oportunidades para aplicações industriais destes produtos, bem como o seu potencial para iniciativas de tecnologia social, particularmente no contexto da agricultura familiar. A produção sustentável de produtos fermentados nativos na Amazônia é vista como um meio de preservar a biodiversidade, capacitar as comunidades locais e promover o patrimônio cultural. O artigo conclui que tanto as tecnologias industriais como as sociais têm papéis complementares na promoção do crescimento económico, na preservação cultural e no bem-estar da região Amazónica, tornando-a um centro promissor para produtos alimentares fermentados inovadores e sustentáveis à escala global.

Palavras-chave: Amazônia, fermentações, tecnologia industrial, tecnologia social, bioeconomia.

1. Introduction

Fermentation plays a pivotal role in the production of essential foods and the global economy. Fermented products such as chocolate, bread, wine, cheese, and yogurt are central to daily diets, prized for their sensory qualities and nutritional benefits (Das et al., 2022). Historical evidence reveals that cereal fermentation has existed for millennia, with figures like Pasteur identifying microorganisms as fermentation agents, reinforcing the significance of this practice over time (Şanlier et al., 2019; Wang et al., 2021; Cavaillon and Legout, 2022; Cuamatzin-García et al., 2022; Wu et al., 2023).

These fermentative processes, including alcoholic, acetic, and lactic fermentation, yield pathogen-free foods,

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ensuring food safety and extending product shelf life due to their antimicrobial properties. Today, the modern industry continues to explore fermented products not only for their taste and digestibility but also for their potential as sources of beneficial probiotics that promote intestinal health and human well-being (Zommiti et al., 2020; Voidarou et al., 2020; Baillo et al., 2023).

In Latin America, rich in cultural traditions, fermentations play a significant role, with foods like puba, tucupi, tiquira, caxiri, polvilho azedo, tarubá, and Marajó cheese originating from pre-Columbian civilizations (Campos et al., 2019; Brito et al., 2022). With the growing discourse on bioeconomy and regional development in the Brazilian Amazon, it is vital to explore Amazonian fermentations and their potential as tools to drive regional development. This exploration should consider not only the economic aspects but also the social, cultural, and environmental dimensions (Barros and Albernaz, 2014), recognizing that all these elements are interconnected and play a fundamental role in the well-being of a region.

2. Fermented Products from the Amazon Region

Brazil has a rich cultural diversity, resulting from its historical formation that brought together European, African and indigenous peoples (Santos et al., 2019). This diversity is also reflected in culinary traditions and in fermentative processes with substrates found in the country (Schwan et al., 2017; Jimenez et al., 2022). A recent literature review (Lima et al., 2022) described the main fermented products consumed by the Brazilian population, including native and traditional peoples. Among them are artisanal cheeses, fermented meats such as socol and charqui, non-alcoholic or low-alcohol beverages such as aluá, calugi, tarubá and yakupá, alcoholic beverages such as cachaça, tiquira, caiçuma, cauim and caxiri, and fermented foods based cassava such as puba, water flour, sour cassava starch, and tucupi. Figure 1 depicts the preparation of tucupi, while Figure 2 showcases the stages of Tarubá pulp preparation conducted in a community located in the municipality of Santarém, Pará, Brazil.

Table 1 presents the most commonly used substrates in fermentations, with emphasis on cassava and its varieties, which are widely used as sources of carbohydrates by many native communities in the region. Fermentations conducted by lactic acid bacteria (LAB) and ethanol-fermenting yeasts are the most common types of fermentation observed. The products generated have potential nutritional, probiotic, and cultural value. In this literature review, we will highlight two indigenous fermentations: tucupí and caxiri (Santos et al., 2012; Brito et al., 2019; Campos et al., 2019).

3. Tucupi

Tucupi, a viscous yellow broth derived from the bitter cassava root, is a fundamental ingredient in Amazonian cuisine, prominently featured in dishes like tacacá, pato no tucupi, and caruru (Costa et al., 2018). This culinary

Figure 1. Preparation of tucupi in a community in the city of Santarém, Pará, Brazil. (A) Harvested cassava; (B) Grated and sifted cassava; (C, D) Use of tipiti for pressing and extracting the milky liquid; (E, F) Simmering tucupi for 30 to 60 minutes.

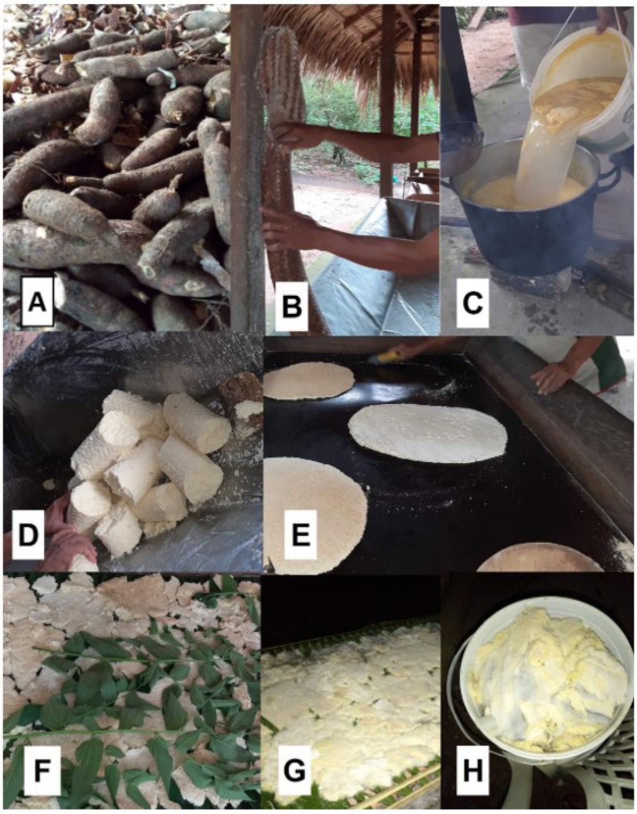

Figure 2. Stages of Tarubá pulp preparation carried out in a community in the city of Santarém, Pará, Brazil. (A) Harvested mandicoca; (B, C) Extracting the liquid part (tucupi) from the mandicoca using tipiti; (D, E) Obtaining the cassava dough and preparing beiju; (F, G) Preparing the bed for fermenting the beijus with curuá palm (*Orbignya pixuna*) leaves and curumim plant; (H) Tarubá dough stored in buckets for commercialization.

gem is celebrated not only for its flavor but also for its nutritional richness, boasting vitamins B and C, along with recognized antioxidant properties (Campos et al., 2019; Brito et al., 2022; Jimenez et al., 2022). In the Amazon region, the annual tucupi production reaches approximately 800,000 liters, with Manaus serving as its primary hub, facilitated by a network of rural producers and artisans who significantly contribute to the local economy (Chisté et al., 2007).

The production process of tucupi, illustrated in Figure 3, commences with the peeling and grating of bitter cassava roots, followed by pressing to extract the milky yellow liquid. This liquid is allowed to rest in large clay bowls for about three days, where natural fermentation takes place, leading to a reduction in cyanide content (Roman, 2022). Throughout the fermentation process, the involvement of lactic acid bacteria, such as *Lactobacillus fermentum* and *Lactobacillus plantarum*, is essential, as they convert the starch found in cassava into lactic acid, bestowing the final product with its characteristic acidic flavor (Brito et al., 2022; Carboni et al., 2023). Furthermore, aerobic mesophilic bacteria, molds and yeasts present in tucupi contribute to the complexity of taste and aroma, generating organic acids like acetic acid and butyric acid (Costa et al., 2018; Campos et al., 2019; Jimenez et al., 2022).

The fermented tucupi (as depicted in Figure 1) resulting from this intricate process is a yellow liquid replete with starch, vitamins, and minerals. It is distinguished by a bitter and pungent flavor, and it is a staple in the cuisine of Northern Brazil, particularly in the creation of the iconic tacacá (Chisté et al., 2007). Beyond its regional significance, tucupi has garnered international recognition, finding its way into the culinary creations of renowned chefs worldwide due to its exotic sensory qualities (Carmo Brito et al., 2019). Tucupi boasts notable nutritional value, characterized by high levels of carbohydrates, fiber, calcium, and iron. Additionally, it serves as a natural source of probiotics that promote intestinal flora balance, further solidifying its status as an indispensable ingredient in the regional cuisine of Northern Brazil (Chacón Mayorga et al., 2021).

Tucupi fermentation varies across locations due to environmental factors, local microbiota, and traditional practices (Carvalho et al., 2019). Key elements contributing to this variability include: 1) Local microbiota, shaped by the region's flora and fermentation practices, impacting flavors and textures. 2) Environmental conditions (climate, temperature, humidity, and water quality) in the Amazon region influencing unique microorganism strains during fermentation. 3) Differences in bitter cassava roots, the

Table 1. Information about fermentation products of native and traditional people of the Brazilian Amazon previously described in the literature.

Name	Substrate	Microorganism	Process	References
Cauim	Cassava and sweet potato. May also contain rice, corn and peanuts	*Lactobacillus pentosus*, *L. plantarum*, *Corynebacterium xerose*, *C. amylocolatum*, *C. vitarumen*, *Bacillus cereus*, *B. licheniformis*, *B. pumilus*, *B. circulans* and *Paenibacillus macerans*	The sun-dried puba is grated and cooked to produce a porridge which, after adding chewed sweet potato, is left to ferment.	Almeida et al. (2007)
Yakupa	Cassava and sweet potato.	*Lactobacillus fermentum*, *L. plantarum*, *Weissela cibaria*, *W. confusa*, *Saccharomyces cerevisiae* and *Pichia kudriavzevii*	The sun-dried puba is mashed, dissolved in water and filtered to remove the fibers. The resulting liquid is cooked and added with grated sweet potato and put to ferment.	Freire et al. (2015)
Caxiri	Cassava and sweet potato. May also contain corn.	*Bacillus pumilus*, *Bacillus cereus*, *Bacillus subtilis*, *Sphingomonas sp*, *Pediococcus acidilactici*, *Saccharomyces cerevisiae*, *Rhodotorula mucilaginosa*, *Pichia membranifaciens*, *Pichia guilliermondii* and *Cryptococcus luteolus*	Roasted puba is mixed with water and grated sweet potato and left to ferment.	Santos et al. (2012) Miguel et al. (2015)
Tarubá	Cassava	*Lactobacillus plantarum, L.brevis, Leuconostoc mesenteroides, Bacillus subtilis, Torulaspora delbrueckii, Pichia* exigua, *Candida rugosa*, *C. tropicalis*, *Pichia kudriavzevii*, *Wickerhamomyces anomalus* and *C. ethanolica*	The cassava mass is first fermented and then diluted in water.	Ramos et al. (2015)
Farinha dágua	Cassava	*Lactobacillus spp*, *Streptococcus spp*, *Candida castellii*, *C. ethanolica, C. krusei*, *Pichia membranifaciens* and *Trichosporon asahii*	For the production of flour, the puba is grounded, pressed and roasted.	Chisté and Cohen (2011)
Tucupi	Cassava	*Lactobacillus fermentum*, *L. plantarum* and low amounts of aerobic mesophilic bacteria, molds and yeasts.	Manipueira (liquid obtained from pressing the grated cassava root) is left to ferment spontaneously for about 24 hours. At the end the fermented liquid is boiled for 30 to 60 min.	Campos et al. (2019) Brito et al. (2022)
Queijo do Marajó	Milk	*Weissella* sp., *Streptococcus* sp., *Lactococcus* sp., *Leuconostoc* sp, *Pediococcus* sp, *Lactobacillus* sp, and *Enterococcus* sp	Buffalo milk is spontaneously fermented to produce a curd that is mixed with cream or butter and then cooked until it produces a homogeneous texture.	Figueiredo et al. (2018) Cruz et al. (2020)
Calugi	Cassava, corn and sweet potato	*Corynebacterium variabile*, *Lactobacillus paracasei*, *L. plantarum*, *L. casei*, *Bacillus cereus*, *B. subtilis*, *Streptomyces sp*, *Enterobacter cloacae*, *Streptococcus parasanguis*, *Streptococcus salivarius*, *Weissella cibaria* and *Weissella confusa.*	Cassava roots are grated and squeezed to produce a wet mass that is cooked together with corn flour and water. After cooling, chewed sweet potato is added and left to ferment.	Miguel et al. (2015)
Tiquira	Cassava	*Aspergillus niger*, *A. flavus*, *Rhizopus oryzae*, *Saccharomyces cerevisia.*	The beiju (cassava bread) is saccharified and fermented simultaneously by the action of native fungi and later distilled	Savadogo et al. (2016) Ribeiro et al. (2019)

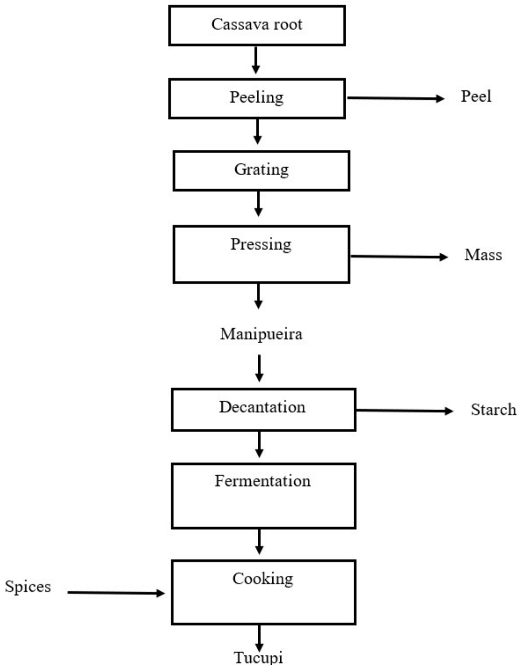

Figure 3. Flowchart showing the production of tucupi by the traditional process
Source: Adapted from Brito et al. (2022).

raw material, affecting tucupi quality and organoleptic characteristics. 4) Variation in traditional processing techniques among communities, affecting the sensory profile of tucupi through differences in juice extraction, fermentation time, and the use of natural additives. It is important to highlight that tucupi's variability is not necessarily a disadvantage but rather a characteristic that enriches local cuisine. Each community in the Amazon region can produce its unique tucupi with distinct flavors and aromas (Silva et al., 2023), contributing to the culinary diversity of the region.

Industrial applications of tucupi are primarily found on a regional scale, and its industrial application is still emerging (Costa et al., 2018). However, there are interesting initiatives in the literature to explore the potential of tucupi in broader industrial applications. For instance, Costa et al. (2017) aimed to develop an industrial product using tucupi as the main ingredient, preparing and evaluating the sensory and rheological characteristics of a creamy tucupi paste. The research results showed that all tucupi paste formulations received good sensory acceptance (>70%). The concentrated creamy tucupi paste (10%) had similar color and acidity to liquid tucupi, and 99% of consumers expressed an intention to purchase. The authors concluded that the creamy tucupi paste presented itself as a promising alternative to traditional tucupi.

Pires (2015) optimized various process parameters for tucupi powder production using the spray dryer method. The physicochemical properties of the resulting tucupi powder, along with its remarkable water solubility, supported the claim that tucupi powder production through the spray dryer method represents a promising perspective for the conservation and commercialization of this product. This was confirmed by Costa et al. (2018), who developed a tucupi powder seasoning and assessed the sensory acceptability of the product. The acceptability index was 80% for overall impression, and the purchase intent test indicated that 94% of the judges would be willing to buy the product. Similar to the production of a creamy tucupi paste, the optimization of the tucupi powder production process plays a crucial role. This optimization is critical as it can open up new market opportunities by increasing product shelf life, reducing weight and volume, which, in turn, significantly contributes to lowering transportation and storage costs, making product distribution to distant regions more efficient (Pires, 2015).

4. Caxiri

Caxiri is a fermented alcoholic beverage of pre-Columbian indigenous origin from the Amazon region, deeply rooted in local culture. Its production is carried out through the fermentation of cassava, which may vary according to the region and ethnic groups involved (Santos et al., 2012; Schwan et al., 2017). Communities such as Belterra, Alter do Chão, Marajó, Barcelos, and Manacapuru are recognized for their large-scale production, although it is difficult to estimate the exact volume due to seasonal and production factors. It is common for these communities to produce caxiri, as the beverage represents an important economic and cultural aspect of the region, being considered a sacred drink for some indigenous tribes in the Amazon and is often consumed in ceremonies and rituals as a form of celebration and communion among members of the tribe (Miguel et al., 2015; Chacón Mayorga et al., 2021).

The caxiri production process (Figure 4) begins with the collection of cassava, which is washed, peeled, and grated. Then, the mass is placed in a sieve and pressed to extract the liquid. This liquid is mixed with water and left to settle. After this, the clear liquid is strained and transferred to a clay pot, where fermentation occurs with the addition of fermenting microorganisms, usually a combination of bacteria and yeasts naturally present in human saliva, and saccharifying amylases (Santos et al., 2012). During the fermentation process, the sugars present in the liquid are converted into alcohol and lactic acid by the microorganisms, including wild yeasts such as *Saccharomyces cerevisiae* and *Candida* sp., as well as lactic acid bacteria such as *Lactobacillus* and *Pediococcus*, and acetic acid bacteria such as *Acetobacter* sp. (Miguel et al., 2015). These microorganisms act synergistically to ferment the sugars present in the cassava broth. The process involves the saccharification of starch, the conversion of sugars into alcohol by yeasts, and the production of lactic acid by lactic acid bacteria, which helps to control the pH of the medium and a suitable environment for yeast growth (Miguel et al., 2015; Tamang and Lama, 2022; Carboni et al., 2023). The flavor/aroma of caxiri is described as slightly bitter and sour, with a touch of sweetness and an earthy taste. Visually, caxiri is a clear drink, with a yellowish or

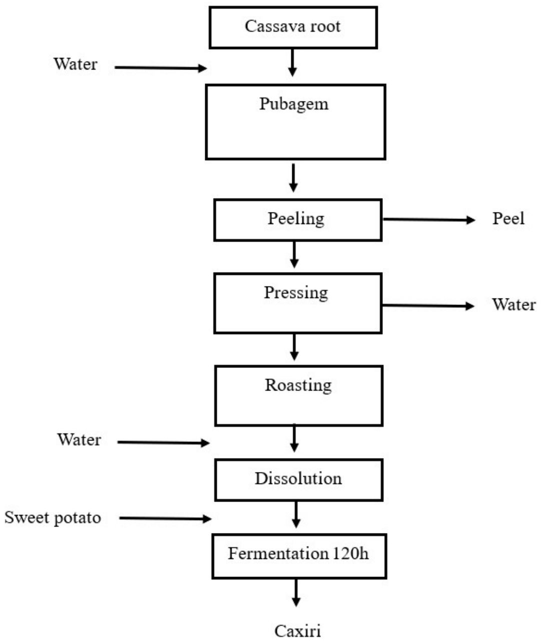

Figure 4. Flowchart showing the production of Caxiri by the traditional process.
Source: Adapted from Santos et al. (2012).

whitish color, and may have a white or beige foam on the surface (Santos et al., 2012).

It is well known that the potential industrial use of caxiri would face significant challenges due to the traditional and artisanal nature of the manufacturing process (Schwan et al., 2017), which differs substantially from large-scale production practices. However, industrialization is not impossible but requires special considerations: process standardization, quality control, production technology, preservation of authenticity, and legal and regulatory issues (Gonçalves et al., 2022. In summary, since the traditional caxiri manufacturing process takes into account specific fermentation practices, local ingredients, and even community involvement (Chacón Mayorga et al., 2021), the degradation of caxiri during industrialization can be a real challenge. Therefore, the industrialization of caxiri should be approached with caution and respect for local culture and traditions, making it more viable to establish partnerships with indigenous communities for small-scale production.

5. Fermented Products from the Amazon Region: Potential for the Food Industry and Social Technology

The Amazon region has a rich history of indigenous innovation and wisdom in the development of unique and highly valued food products, and two notable examples of this success are guaraná and chocolate. Indigenous peoples of the Amazon were the first to cultivate guaraná (*Paullinia cupana*), a plant rich in caffeine. Indigenous knowledge of guaraná cultivation and processing led to a highly valued energy drink, which was later successfully incorporated into the global beverage industry (Figueroa, 2016). The importance of guaraná is evident by its presence on supermarket shelves in the form of soft drinks and energy supplements, and its production is a fundamental part of the local economy in the Amazon (Filoche and Pinton, 2014).

Similarly, the history of chocolate also has deep roots in the indigenous traditions of the Amazon region. Pre-Columbian indigenous peoples, including the Mayans and Aztecs, developed cocoa processing techniques that turned the seeds into a paste enjoyed as a dark and bitter beverage (Coq-Huelva et al., 2017). This tradition was later passed on to European colonizers who refined the chocolate production process and popularized it worldwide (Foster and Cordell, 1992). These products not only exemplify the innovative capacity of indigenous communities in the Amazon but also demonstrate the potential of fermented products from the region for the global market.

Products from the Amazon region have the potential for widespread use in various applications such as condiments, beverages, food preservation, and food additives (Abreu et al., 2020; Prando et al., 2023; Bogas et al., 2022). Furthermore, it is known that products like tucupi and jambu are already widely used as condiments in local cuisine and have the potential for global consumption (Costa et al., 2017). Finally, the fermentation of other native fruits such as cupuaçu, buriti, taperebá, bacuri, camu-camu, and wild bee honey can be used for the large-scale production of fruit wines, beers, and vinegars (Dias et al., 2003; Pelais et al., 2008; Costa et al., 2018; Gonçalves et al., 2022). These examples highlight the remarkable ability of indigenous communities in the Amazon to develop unique and highly valued food products. The appreciation of these indigenous fermented products can not only boost the regional economy but also promote the preservation of traditional practices and sustainability (Garrett et al., 2021). Table 2 describes the environmental, economic, and social advantages of the industrial production of fermented products from the Amazon region.

On the other hand, in recent years, social technology has emerged as an alternative for promoting sustainable development in various regions of the world (Duque and Valadão, 2017; Souza and Pozzebon, 2020). In the Brazilian context, there are several initiatives based on social technologies, ranging from the production of organic food in small rural properties to the implementation of water treatment and basic sanitation systems in needy communities (Oliveira et al., 2022). Taking the production of tucupi as an example of social technology in an Amazonian community, this process would mainly involve family farmers who cultivate cassava, the primary ingredient of tucupi. Production would take place on small rural properties or community associations, and products would be sold at local fairs, cooperatives, and even online, allowing access to distant markets. This social approach has the potential to valorize family farming and protect the region's natural resources (Silva et al., 2022).

The sustainable production of native fermented products in the Amazon can bring many benefits. Firstly, it helps preserve the region's rich biodiversity, as sustainable

Table 2. Environmental, Economic, and Social Advantages of Industrial Production of Fermented Products in the Amazon Region.

Point of View	Advantages	References
Environmental	Incentive for forest conservation, as many of the plants used in fermentation are found in the Amazon rainforest.	Oliveira et al. (2022)
	Encouragement for the adoption of more responsible business practices, due to the increased demand for organic and sustainable products.	Gonçalves et al. (2022)
		Silva et al. (2022)
Economic	More business opportunities for local companies, creating jobs and increasing community income.	Dias et al. (2003)
		Materia et al. (2021)
	Industrial production can enable access to regional, national, and international markets, expanding the reach of Amazonian products and increasing the visibility of the region.	Carboni et al. (2023)
Social	Promotion of cultural tourism, as unique fermented products can attract tourists interested in indigenous culture and regional cuisine.	Lima et al. (2022)
	Reinforcement of local identity, highlighting the value of its traditions and knowledge.	Schwab and Freitas (2016)

practices protect the natural resources used in these products (Lima et al., 2022). Moreover, by valuing native ingredients and traditional knowledge, sustainable production empowers local communities and enhances their economic well-being. It also promotes cultural pride among indigenous and local populations, highlighting the significance of their heritage on the global stage (Oliveira et al., 2022). However, the success of sustainable production depends on effective government support, regulations, and quality control (Schwab and Freitas, 2016). This involvement is essential to ensure the adoption of sustainable practices, product compliance with hygiene and standardization standards, and access to markets beyond their local communities. In summary, sustainable production of native fermented products in the Amazon region offers an opportunity to balance economic growth with environmental conservation, cultural preservation, and the strengthening of local communities (Silva and Begossi, 2009).

6. Conclusion

In conclusion, this review explores how fermentations in the Amazon region can boost economic and social development. We compared two approaches: industrial technology and social technology. It's clear that the Amazon boasts a rich culinary and cultural diversity with ancient food fermentation traditions that remain relatively unknown to the world.

We've found that both industrial and social technologies have their roles to play. Industrial methods are essential for large-scale production and delivering standardized products to the global market. Meanwhile, social technology is vital for preserving cultural traditions, empowering local communities, promoting social inclusion, and reducing inequalities. As global demand for natural and culturally rich products grows, the Amazon stands as an untapped resource. By understanding and respecting indigenous techniques and working closely with local communities, we can replicate the success of guaraná and chocolate, illustrating how Amazonian fermented products can drive innovation and growth in the food industry.

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