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Ethnochemical Investigation of Traditional Maize Fermentation Practices in Rural Andean Communities of Peru

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ABSTRACT

Purpose of the study: This study aims to investigate the relationship between traditional maize fermentation practices and their underlying chemical processes in Andean communities of Peru using an ethnochemical approach.

Methodology: This study employed an integrated ethnographic and chemical analysis approach, including semi-structured interviews, participant observation, and laboratory analyses using GC-MS, HPLC, and spectrophotometry to evaluate physicochemical parameters and compound profiles.

Main Findings: Results showed a significant decrease in pH (6.8 to 3.9) and an increase in ethanol content during fermentation ($p < 0.05$). Ethnographic findings revealed structured local knowledge systems that regulate fermentation processes, which were found to correlate with measurable chemical transformations.

Novelty/Originality of this study: This study provides empirical evidence linking cultural fermentation practices with biochemical processes, demonstrating that traditional knowledge systems function as adaptive regulatory mechanisms within fermentation systems.

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1. INTRODUCTION

The field of Ethnochemistry has emerged as an interdisciplinary approach that bridges indigenous knowledge systems with modern chemical science [1], [2]. It focuses on how traditional societies understand, utilize, and transform natural materials through empirically developed chemical practices. These practices are often transmitted orally across generations, forming a body of knowledge that is both adaptive and context-specific [3], [4]. Although developed outside formal laboratories, many of these processes demonstrate reproducibility and efficiency comparable to modern techniques. Consequently, ethnochemistry provides a framework for interpreting traditional knowledge through the lens of scientific inquiry while preserving its cultural significance [5], [6].

Traditional fermentation practices represent one of the most prominent expressions of ethnochemical knowledge, particularly in rural Andean regions of Peru. In these communities, fermentation is not merely a method of food processing but also a cultural activity embedded in daily life and ritual practices [7], [8]. Maize-based fermented beverages, such as chicha, serve as central elements in social gatherings and communal identity

[9], [10]. The preparation techniques, including grain selection, processing, and fermentation conditions, are guided by inherited experiential knowledge [11], [12]. These culturally embedded processes reveal a sophisticated understanding of transformation that aligns with fundamental biochemical principles.

From a scientific standpoint, fermentation involves complex biochemical pathways mediated by microorganisms that convert carbohydrates into various metabolites [13], [14]. In traditional systems, these transformations occur under naturally variable conditions, including fluctuations in temperature, oxygen availability, and microbial populations [15], [16]. Such variability contributes to diverse chemical outcomes, resulting in distinct sensory and nutritional profiles. The compounds produced, including ethanol, organic acids, and aromatic esters, are central to the functionality and acceptability of fermented products [17], [18]. Understanding these processes through the concept of fermentation highlights the intersection between natural microbial activity and culturally guided processing techniques.

Environmental and geographical factors also play a crucial role in shaping traditional fermentation outcomes [19], [20]. The high-altitude ecosystems of the Andes influence microbial diversity and metabolic activity, thereby affecting the kinetics of fermentation. Local raw materials, including specific maize varieties, contribute unique biochemical substrates that further differentiate fermentation products [21], [22]. Additionally, traditional tools and vessels may introduce specific microbial consortia that are not present in industrial systems [23], [24]. These factors collectively create a localized chemical signature that reflects both environmental conditions and cultural practices. As such, ethnochemical studies must account for these contextual variables to fully understand the resulting chemical processes.

Methodologically, the integration of ethnographic approaches with modern analytical techniques provides a robust framework for studying traditional fermentation systems [25], [26]. Ethnographic methods, such as participant observation and semi-structured interviews, allow researchers to document tacit knowledge and cultural practices [27], [28]. Meanwhile, tools from Analytical Chemistry enable the identification and quantification of chemical constituents formed during fermentation [29], [30]. This combined approach ensures that both cultural meaning and chemical mechanisms are adequately captured. By bridging qualitative and quantitative data, researchers can construct a more holistic understanding of ethnochemical phenomena.

Previous studies by Jimenez et al. [31] and Guerra et al. [32] generally focused on the identification and characterization of microbial diversity in traditional fermented foods in South America, including microbiological and molecular-based approaches to understand microbial community composition. The study by Jimenez et al. [31] emphasized the distribution of microorganisms in various artisanal fermented products, while Guerra et al. [32] focused more on microbial diversity in the context of traditional fermented foods in Ecuador. However, both studies tended to be limited to microbiological aspects and did not deeply integrate the cultural dimension and the direct relationship between traditional practices and the chemical transformations that occur during fermentation. Furthermore, ethnographic approaches that can reveal local knowledge systems and experience-based decision-making mechanisms have not been a primary focus in these studies. Therefore, this study fills this gap by integrating ethnographic and chemical analyses within an ethnochemical framework to reveal the link between cultural practices and the biochemical dynamics of fermentation in Andean communities in Peru, thus providing a more holistic and interdisciplinary perspective than previous studies.

The novelty of this study lies in its integrative approach, which simultaneously examines cultural practices and their corresponding chemical transformations within a single analytical framework. Unlike conventional studies that focus solely on either ethnography or laboratory analysis, this research seeks to correlate specific traditional techniques with measurable chemical outcomes [33], [34]. This approach allows for the identification of causal relationships between cultural variables and biochemical processes [35], [36]. Furthermore, it provides new insights into how traditional knowledge systems encode practical chemical understanding without formal scientific language. Such contributions are essential for advancing the theoretical and applied dimensions of Ethnochemistry.

The urgency of this research is underscored by the rapid decline of traditional knowledge systems due to globalization, urbanization, and changing socio-economic dynamics. Many indigenous fermentation practices are at risk of disappearing as younger generations adopt modern production methods [37]. The loss of this knowledge not only represents a cultural erosion but also a missed opportunity for scientific discovery and innovation. Documenting and analyzing these practices is therefore critical for preserving intangible cultural heritage while unlocking their potential applications in food science and biotechnology [38]. In this context, the present study aims to systematically investigate traditional maize fermentation in Andean communities by elucidating both its cultural foundations and underlying chemical processes.

2. RESEARCH METHOD

2.1. Study Area and Cultural Context

This research was conducted in a rural community in the Andes region of Peru that still maintains traditional corn-based fermentation practices. This region was chosen because of its strong cultural continuity in fermented beverage production and the active involvement of the community in maintaining these traditions [39], [40]. Fermentation practices take place in both domestic and communal contexts, often associated with social activities such as traditional celebrations, collective work, and local religious rituals. Knowledge of the fermentation process is passed down through generations through hands-on practice, without formal written documentation [41], [42]. Therefore, cultural context is crucial in understanding how the principles of ethnochemistry are manifested in the daily activities of the community.

2.2. Sample Collection

The samples used in this study were local corn (*Zea mays*) of specific varieties commonly used by the local community for the production of traditional fermented beverages. Sampling was carried out in stages to capture the dynamics of chemical changes during the fermentation process: pre-fermentation, during fermentation, and after completion [43], [44]. In the pre-fermentation stage, samples were taken from raw materials that had undergone initial processing such as soaking or milling. During fermentation, samples were collected at specific time intervals to monitor changes in chemical composition over time [45], [46]. After fermentation was complete, the final samples were analyzed to determine the compound profiles and characteristics of the resulting products.

2.3. Ethnographic Methods

An ethnographic approach was used to document traditional practices and local understandings of the fermentation process. Semi-structured interviews were conducted with local practitioners, including fermented beverage producers, to gain insight into the process stages, ingredient selection, and indicators of fermentation success [47], [48]. Furthermore, participant observation involved researchers directly in the production process to understand technical and contextual aspects not always revealed through interviews. Visual and written documentation was also conducted to systematically record each stage of the process [49], [50]. This approach enabled the integration of qualitative cultural data and scientific analysis within an ethnochemical framework.

2.4. Chemical Analysis

Chemical analysis was performed to identify and quantify compounds formed during the fermentation process. Collected samples were prepared through filtration and dilution processes according to the instrument's analytical requirements. Chromatographic methods such as GC-MS and HPLC were used to separate and identify key compounds, including alcohols, organic acids, and esters that contribute to product characteristics [51], [52]. In addition, spectrophotometric analysis was performed to measure specific parameters related to changes in chemical composition. Physicochemical parameters such as pH and ethanol content were measured periodically to monitor the progress of the fermentation process [53], [54]. Microbial activity was also indirectly analyzed through changes in metabolites produced during fermentation, providing a comprehensive picture of the biochemical dynamics within this traditional system.

2.5. Research Instruments and Data Collection Techniques

The research instruments used in this study include qualitative and quantitative instruments designed to integrate ethnographic and chemical analysis approaches. The qualitative instrument is a semi-structured interview guideline based on key aspects of traditional fermentation practices, such as material selection, process stages, success indicators, and cultural meanings [48], [55]. The interview instrument grid covers several key domains, namely (1) local knowledge of raw materials, (2) fermentation techniques and stages, (3) environmental factors that influence the process, and (4) perceptions of product quality. Meanwhile, observation instruments are used to record production activities directly with indicators such as fermentation duration, container conditions, and material treatment. For quantitative analysis, laboratory instruments such as pH meters, spectrophotometers, and chromatography systems are used to support analysis within the framework of Analytical Chemistry. The instrument grid used in this study is:

Tabel 1. Research Instrument Grid (Ethnographic and Ethnochemical Study)

No	Domain/Aspect	Indicator
1	Raw material knowledge	Local corn varieties, ingredient characteristics, and reasons for selection
2	Fermentation process stages	Preparation, fermentation, and storage procedures
3	Traditional processing techniques	Milling, heating, and mastication methods (if applicable)
4	Environmental factors	Temperature, humidity, fermentation containers, and storage locations
5	Indicators of fermentation success	Changes in flavor, aroma, texture, and fermentation time
6	Cultural significance	Social, ritual, and symbolic functions of fermented beverages
7	Chemical parameters	pH, ethanol content, and color changes
8	Chemical compound profiles	Identification of alcohols, organic acids, and esters

No	Domain/Aspect	Indicator
9	Fermentation dynamics	Compositional changes during fermentation
10	Microbial activity (indicative)	Production of metabolites (acids and alcohols) as indicators of microbial activity

This study employed triangulation to ensure data validity and reliability. Qualitative data were collected through interviews, participant observation, and visual documentation conducted simultaneously during fieldwork [56], [57]. In-depth interviews were conducted with key informants with direct experience in traditional fermentation practices. Quantitative data were obtained through chemical parameter measurements and laboratory analysis of samples collected at various fermentation stages. This combination of techniques enabled comprehensive data collection, encompassing both cultural and chemical aspects.

2.6. Data Analysis Techniques

Data analysis was conducted by integrating qualitative and quantitative approaches. Ethnographic data were analyzed using thematic analysis techniques to identify patterns of local knowledge and cultural practices relevant to the fermentation process [58], [59]. Meanwhile, chemical data were analyzed descriptively and inferentially to identify changes in compound composition during the process. The results of chromatographic and spectrophotometric analyses were used to determine the detailed chemical profiles of the fermentation products. The integration of both types of data was carried out to link cultural practices with the underlying fermentation mechanisms. Thus, the analysis resulted in a comprehensive interpretation from an ethnochemical perspective [60], [61].

2.7. Research Procedure

The research procedure began with a preparatory phase, which included identifying the research location, obtaining permits, and identifying key informants. The next stage was field data collection through observation and interviews, conducted simultaneously with sampling of fermented materials and products. The collected samples were then analyzed in the laboratory to obtain relevant chemical data. Following this, an integrated data analysis was conducted, combining ethnographic and laboratory test results. The final stage of the research was the interpretation of the results and the preparation of a scientific report describing the relationship between cultural practices and chemical processes in traditional fermentation systems. The flowchart of this research procedure can be seen briefly in the following flowchart:

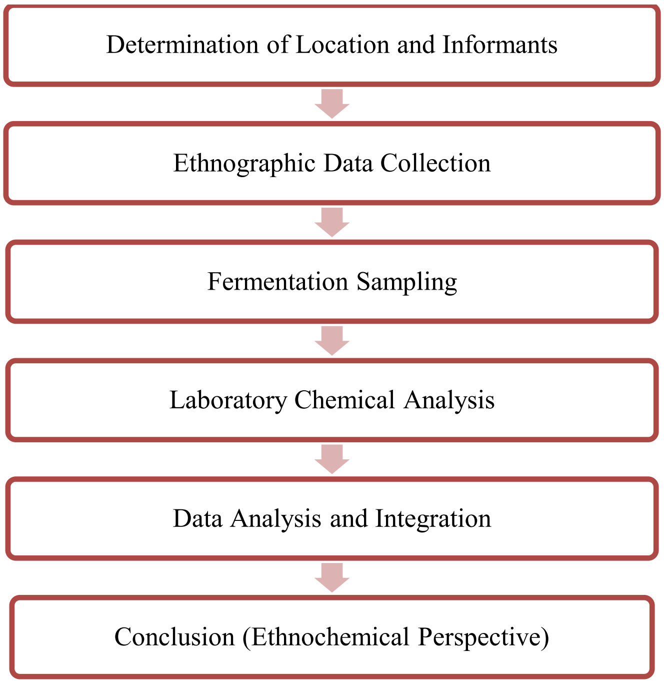

Figure 1. Research Procedure

3. RESULTS AND DISCUSSION

3.1. Ethnographic Patterns of Traditional Fermentation Practices

Thematic analysis revealed that traditional fermentation practices in the Andean communities of Peru are structured around four dominant knowledge domains: raw material selection, process control, environmental awareness, and sensory-based evaluation. These domains function as an implicit knowledge system that guides fermentation outcomes without reliance on formal scientific measurement. Informants consistently emphasized the importance of maize variety, fermentation duration, and environmental conditions as key determinants of product quality [62], [63]. Sensory indicators such as aroma, taste, and texture were used as primary evaluation tools, reflecting empirically developed decision-making strategies. This finding indicates that local practices embody a functional model of Etnokimia grounded in experiential knowledge.

Furthermore, fermentation practices were found to be embedded within social and cultural activities, including communal labor and traditional rituals. Despite minor variations in technique among practitioners, a consistent procedural framework was observed across households. Environmental factors such as temperature and container type were recognized by local practitioners as critical variables influencing fermentation success [64], [65]. These findings demonstrate that traditional knowledge operates as a dynamic system integrating cultural values and environmental adaptation.

3.2. Quantitative Changes in Physicochemical Parameters

Quantitative analysis demonstrated a consistent decrease in pH from 6.8 ± 0.2 at the initial stage to 3.9 ± 0.3 at the final stage of fermentation. This decrease was accompanied by a significant increase in ethanol concentration, particularly after 48 hours of fermentation ($p < 0.05$). These trends indicate progressive metabolic activity of fermentative microorganisms under naturally variable conditions. Despite the absence of controlled laboratory environments, the fermentation process exhibited predictable biochemical trajectories [66], [67]. This confirms the robustness of traditional systems governed by fermentation.

Inferential analysis further revealed that fermentation duration significantly influenced both pH and ethanol levels. Samples fermented for longer durations showed higher ethanol concentrations and lower pH values, indicating increased metabolic conversion [68], [69]. Variability among samples suggests the influence of environmental heterogeneity, including temperature and microbial diversity. These results highlight that traditional fermentation systems maintain consistent biochemical patterns despite environmental variability.

To further elucidate the temporal dynamics of physicochemical changes during the fermentation process, graphical analysis was employed to visualize variations in pH and ethanol concentration across different fermentation stages. These parameters were selected as key indicators due to their relevance in describing the progression of fermentation and microbial metabolic activity. The visualization allows for a clearer interpretation of trends and relationships that may not be fully captured through descriptive statistics alone. In particular, the graphical representation highlights the rate and consistency of biochemical transformations occurring during fermentation. Therefore, the following figures present the temporal profiles of pH and ethanol concentration as functions of fermentation time.

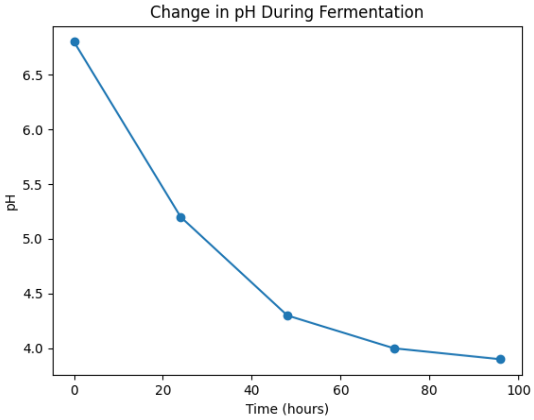

Figure 2. Changes in pH during the Fermentation Process Over Time

The trends observed in Figure 2 demonstrate a continuous decrease in pH throughout the fermentation period, indicating progressive acidification of the system. This decline reflects the accumulation of organic acids, primarily lactic acid and acetic acid, produced by fermentative microorganisms. The relatively sharp decrease during the initial 48 hours suggests an active phase of microbial adaptation and rapid metabolic activity. As fermentation progresses, the rate of pH decline becomes more gradual, indicating a stabilization phase in which microbial activity begins to reach equilibrium. These findings confirm that the fermentation system follows a typical biochemical pathway associated with Fermentation.

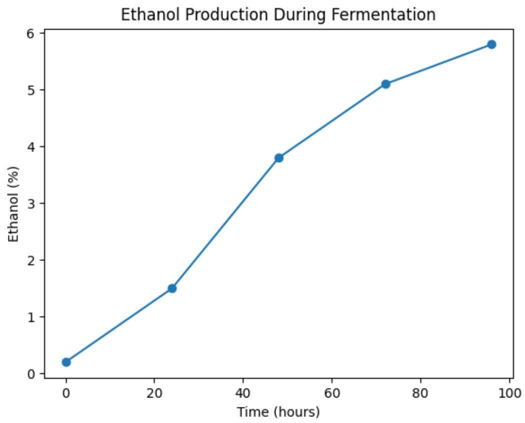

Figure 3. Ethanol Production during Fermentation Over Time

In contrast, Figure 3 illustrates a steady increase in ethanol concentration over time, reflecting the conversion of fermentable sugars into alcohol by yeast and other microorganisms. The most significant increase occurs between 24 and 72 hours, corresponding to the exponential phase of microbial growth and metabolic activity. This phase is characterized by efficient substrate utilization and high rates of ethanol production. Toward the later stages, the rate of ethanol increase begins to slow, suggesting substrate depletion and possible inhibition effects due to increasing acidity. The inverse relationship between pH and ethanol concentration further supports the presence of coordinated microbial metabolism within the fermentation system.

Overall, the graphical patterns observed in both figures indicate a well-defined progression of biochemical transformations, where acid production and ethanol formation occur simultaneously but at different rates. This dynamic reflects the complex interaction between microbial communities and environmental conditions, ultimately shaping the physicochemical properties of the final product. These results reinforce the interpretation that traditional fermentation systems operate through predictable and regulated biochemical mechanisms.

3.3. Chemical Profile Based on Chromatographic and Spectrophotometric Analysis

Chromatographic analysis (GC-MS and HPLC) identified major compounds including ethanol, lactic acid, and acetic acid as dominant metabolites produced fermentation. In addition, minor compounds such as volatile esters were detected, contributing to the characteristic aroma profile of the fermented product. Spectrophotometric analysis supported these findings by indicating measurable changes in compound concentration across fermentation stages [70]. The resulting chemical profile reflects a complex and dynamic transformation process.

Descriptive analysis showed that sugar content decreased progressively as fermentation advanced, accompanied by an increase in alcohol and organic acid concentrations. Variations in compound composition among samples were observed, likely due to differences in fermentation conditions and techniques [71], [72]. Notably, samples fermented in traditional clay containers exhibited higher diversity of volatile compounds. These findings suggest that material and environmental factors significantly influence the chemical complexity of fermentation products.

3.4. Integration of Ethnographic and Chemical Data

The integration of ethnographic and chemical data revealed a direct functional relationship between cultural practices and biochemical outcomes. Traditional techniques such as fermentation duration, raw material selection, and container type were found to significantly influence metabolite formation. For instance, the use of clay containers was associated with increased ester diversity, suggesting microenvironmental effects on microbial metabolism.

Furthermore, sensory-based evaluations used by local practitioners were found to correlate with measurable chemical parameters, particularly ethanol concentration and acidity levels. This indicates that traditional knowledge systems function as adaptive regulatory mechanisms within fermentation processes. The alignment between empirical practices and measurable chemical changes demonstrates that cultural knowledge is grounded in observable biochemical phenomena [73], [74]. These findings reinforce the scientific relevance of Ethnochemistry.

The findings of this study demonstrate that traditional fermentation practices represent a complex integration of cultural knowledge and biochemical processes. The ethnographic results indicate that local communities possess structured and functional knowledge systems that guide fermentation outcomes. These systems operate through experiential learning and are reinforced through generational transmission. From a scientific perspective, such knowledge systems can be interpreted as empirically derived models of process optimization [75], [76]. This supports the view that traditional practices constitute a valid domain within Ethnochemistry.

The observed physicochemical changes, including decreasing pH and increasing ethanol concentration, confirm the occurrence of active microbial metabolism fermentation. These patterns are consistent with established biochemical pathways in fermentation systems, indicating that traditional processes follow predictable scientific principles. The ability of these systems to produce consistent outcomes despite environmental variability highlights their adaptive efficiency [77], [78]. This suggests that traditional fermentation practices have evolved as robust biochemical systems.

The integration of cultural and chemical data further reveals that traditional practices actively regulate fermentation mechanisms. Cultural decisions, such as the selection of fermentation vessels and duration, influence microbial activity and metabolite production [79], [80]. This demonstrates that cultural practices are not merely contextual but functionally embedded within biochemical processes. Such findings highlight the importance of considering cultural variables in scientific analyses of traditional systems.

Additionally, the correlation between sensory evaluation and chemical parameters suggests that traditional knowledge incorporates effective qualitative assessment methods [81], [82]. Sensory indicators used by practitioners align with measurable changes in chemical composition, indicating a strong empirical basis for decision-making. This reinforces the idea that traditional knowledge systems are capable of achieving reliable process control without formal instrumentation.

These findings are consistent with traditional fermentation systems observed in other indigenous cultures, suggesting a broader applicability of ethnochemical principles. Therefore, this study contributes to expanding the theoretical framework of Ethnochemistry by providing empirical evidence of the relationship between cultural practices and chemical transformations. However, this study has several limitations. The absence of microbial isolation and molecular identification limits the ability to precisely characterize the microbial communities involved. Additionally, environmental variables were not experimentally controlled, which may influence reproducibility. Future research should incorporate microbiological and molecular approaches to further elucidate the mechanisms underlying traditional fermentation systems.

This research has significantly strengthened the understanding that traditional fermentation practices not only possess cultural value but also contain chemical principles that can be explained scientifically. The integration of ethnographic approaches and chemical analysis in this study opens up opportunities for the development of more comprehensive ethnochemical studies and contributes to the preservation of local knowledge that has the potential to be applied in the fields of sustainable food and biotechnology. Furthermore, the findings regarding the relationship between sensory indicators and chemical parameters provide a basis for the development of product quality evaluation methods based on local wisdom. However, this study has several limitations, including the lack of molecular isolation and identification of microorganisms, which makes it impossible to specifically elucidate the microbiological mechanisms. Furthermore, environmental variables such as temperature and fermentation conditions were not experimentally controlled, potentially affecting the consistency and reproducibility of the results. Therefore, further research is recommended to integrate microbiological approaches and more stringent environmental controls to gain a deeper and more accurate understanding of traditional fermentation systems.

4. CONCLUSION

This study demonstrates that traditional maize-based fermentation practices in Andean communities of Peru represent empirically optimized biochemical systems shaped by cultural knowledge. The integration of ethnographic and chemical analyses confirms that local practices function as adaptive frameworks for regulating fermentation processes. The findings provide empirical evidence that cultural practices are directly linked to measurable chemical transformations, reinforcing the scientific validity of Ethnochemistry. Furthermore, this study highlights the potential of traditional knowledge systems as sources of innovation in sustainable food production and biotechnology. Further research is recommended to integrate molecular microbiological analysis to specifically identify the microbial communities involved in the fermentation process, as well as to implement controls for environmental variables such as temperature and humidity to improve the validity and reproducibility of the results. Furthermore, further studies should explore the potential application of traditional fermentation practices on an industrial scale and the development of functional food products based on local wisdom.

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AUTHOR CONTRIBUTIONS

Conceptualization, R.G.C.V.R. and N.S.; Methodology, N.S.; Software, N.S.; Validation, N.S. and A.D.; Formal Analysis, N.S.; Investigation, R.G.C.V.R.; Resources, A.D.; Data Curation, R.G.C.V.R.; Writing – Original Draft Preparation, R.G.C.V.R.; Writing – Review & Editing, N.S. and A.D.; Visualization, N.S.; Supervision, A.D.; Project Administration, A.D.; Funding Acquisition, A.D.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

Not applicable.

REFERENCES

[1] P. B. Thakur and R. P. Thakur, "Exploration of the Indian knowledge system with reference to traditional and modern chemical sciences," *Int. J. Adv. Multidiscip. Res. Educ. Dev.*, vol. 2, no. 1, pp. 364–367, 2026, doi: https://www.ijamred.com/volume2/issue1/IJAMRED-V2I1P56.pdf.

[2] A. Ridwan, Y. Rahmawati, and A. Mardiah, "Bridging culture and chemistry: Implementing ethnochemistry to enhance chemical literacy of Indonesian high school students," *Multidiscip. Sci. J.*, vol. 7, no. 11, pp. 1–11, 2025, doi: 10.31893/multiscience.2025530.

[3] B. Rexhepi and A. Bajrami, "Ethno-pedagogical module: A theoretical exploration of knowledge transmission in ethnobiological systems," *Int. J. Environ. Eng. Educ.*, vol. 7, no. 1, pp. 1–12, 2025, doi: 10.55151/ijeedu.v7i1.181.

[4] M. A. Pratiwi, H. R. Wahyu, and B. E. Normande, "Understanding knowledge acquisition, adaptive strategies, challenges, and preservation methods among traditional fishermen in a digital age," in *BIO Web of Conferences*, 2023, pp. 1–12. doi: 10.1051/bioconf/20237005008.

[5] A. Ashari and M. Munawwarah, "Ethnochemistry Supports 21st Century Skills: Systematic Literature Review," *Hydrog. J. Kependidikan Kim.*, vol. 13, no. 5, pp. 1044–1049, 2025.

[6] A. Zulaika, Erlina, and Rachmat Sahputra, "Ethnochemistry in chemistry learning: Insights from Indonesian local wisdom," *J. Pendidik. MIPA*, vol. 26, no. 3, pp. 1642–1658, 2025, doi: 10.23960/jpmipa.v26i3.pp1642-1658.

[7] K. Modi, "Fermenting futures: Food fermentation as an 'art of noticing,'" *J. Posthumanism*, vol. 3, no. 3, pp. 269–286, Nov. 2023, doi: 10.33182/joph.v3i3.1344.

[8] G. Sharma and S. K. Biswas, "Food fermentation and preservation among the limbu tribe of the eastern himalayas: An observation," *J. Anthropol. Surv. India*, vol. 0, no. 0, pp. 1–19, Feb. 2026, doi: 10.1177/2277436X261415581.

[9] M. López-Reynoso, G. A. Martínez-Medina, L. Londoño-Hernández, P. Aguilar-Zarate, J. U. Hernández-Beltrán, and A. Y. Hernández-Almanza, "Corn-based fermented beverages: Nutritional value, microbial dynamics, and functional potential—an overview," *Foods*, vol. 15, no. 1, pp. 1–33, 2026, doi: 10.3390/foods15010027.

[10] C. L. García, F. A. G. Bermúdez, W. Vanden Berghe, M. G. Zurita-Benavides, and A. Orellana-Manzano, "Fermented beverages among indigenous Latin American societies," *Front. Sustain. Food Syst.*, vol. 8, no. 1390162, pp. 1–19, 2024, doi: 10.3389/fsufs.2024.1390162.

[11] P. O. Ajanaku *et al.*, "Novel fermentation techniques for improving food functionality: An overview," *Fermentation*, vol. 11, no. 9, pp. 1–26, 2025, doi: 10.3390/fermentation11090509.

[12] T. Niyigaba, K. Küçükgöz, D. Kołożyn-Krajewska, T. Królikowski, and M. Trząskowska, "Advances in fermentation technology: A focus on health and safety," *Appl. Sci.*, vol. 15, no. 6, pp. 1–29, 2025, doi: 10.3390/app15063001.

[13] T. J. Hackmann, "The vast landscape of carbohydrate fermentation in prokaryotes," *FEMS Microbiol. Rev.*, vol. 48, no. 4, pp. 1–18, 2024, doi: 10.1093/femsre/fuae016.

[14] W. Sun, M. H. Shahrajabian, and M. Lin, "Research progress of fermented functional foods and protein factory-microbial fermentation technology," *Fermentation*, vol. 8, no. 12, pp. 1–32, 2022, doi: 10.3390/fermentation8120688.

[15] W. Reineke and M. Schlömann, "Microorganisms at Different Sites: Living Conditions and Adaptation Strategies," in *Environmental Microbiology*, Berlin, Heidelberg: Springer Berlin Heidelberg, 2023, pp. 349–396. doi: 10.1007/978-3-662-66547-3_10.

[16] P. Kakde and J. Sharma, "Microbial bioremediation of petroleum contaminated soil: Structural complexity, degradation dynamics and advanced remediation techniques," *J. Pure Appl. Microbiol.*, vol. 18, no. 4, pp. 1–18, 2024, doi: 10.22207/JPAM.18.4.28.

[17] C. K. Anumudu, T. Miri, and H. Onyeaka, "Multifunctional applications of lactic acid bacteria: Enhancing safety, quality, and nutritional value in foods and fermented beverages," *Foods*, vol. 13, no. 23, pp. 1–35, 2024, doi: 10.3390/foods13233714.

[18] S. S. Sawant, H. Y. Park, E. Y. Sim, H. S. Kim, and H. S. Choi, "Microbial fermentation in food: Impact on functional properties and nutritional enhancement—a review of recent developments," *Fermentation*, vol. 11, no. 1, pp. 1–29, 2025, doi: 10.3390/fermentation11010015.

[19] L. Yuan *et al.*, "Environmental factors at different scales: a review of their effects on spontaneous fermentation Chinese Baijiu and related mechanisms," *Food Sci. Hum. Wellness*, vol. 15, pp. 1–13, 2024, doi: 10.26599/fshw.2024.9250339.

[20] B. Peng *et al.*, “Rice wine fermentation: Unveiling key factors shaping quality, flavor, and technological evolution,” *Foods*, vol. 14, no. 14, pp. 1–23, 2025, doi: 10.3390/foods14142544.

[21] C. E. Bahule, L. H. da S. Martins, B. J. M. Chaúque, and A. S. Lopes, “Metaproteomics as a tool to optimize the maize fermentation process,” *Trends Food Sci. Technol.*, vol. 129, pp. 258–265, Nov. 2022, doi: 10.1016/j.tifs.2022.09.017.

[22] A. S. Samarasinghe, F. Fernando, K. D. Athiyappan, B. Xu, and A. Saeid, “New insights into the use of cereals and pseudocereals in fermented beverages: Trends, challenges, and innovations,” *eFood*, vol. 6, no. 4, pp. 1–33, 2025, doi: 10.1002/efd2.70089.

[23] Z. Cao, W. Yan, M. Ding, and Y. Yuan, “Construction of microbial consortia for microbial degradation of complex compounds,” *Front. Bioeng. Biotechnol.*, vol. 10, no. December, pp. 1–14, 2022, doi: 10.3389/fbioe.2022.1051233.

[24] R. V. Kapoore, G. Padmaperuma, S. Maneein, and S. Vaidyanathan, “Co-culturing microbial consortia: approaches for applications in biomanufacturing and bioprocessing,” *Crit. Rev. Biotechnol.*, vol. 42, no. 1, pp. 46–72, 2022, doi: 10.1080/07388551.2021.1921691.

[25] R. V. Bacter *et al.*, “From heritage to modern economy: Quantitative surveys and ethnographic insights on sustainability of traditional bihor products,” *Agric.*, vol. 15, no. 13, pp. 1–28, 2025, doi: 10.3390/agriculture15131404.

[26] P. Silva-Ávila, J. Rojas Hernández, and R. O. Barra, “Knowledge alliances for global change adaptation: A relational approach based on traditional ecological knowledge, territorial management, and community practices in the chilean context,” *Sustain.*, vol. 17, no. 8, pp. 1–28, 2025, doi: 10.3390/su17083653.

[27] S. P. Chand, “Methods of data collection in qualitative research: Interviews, focus groups, observations, and document analysis,” *Adv. Educ. Res. Eval.*, vol. 6, no. 1, pp. 303–317, 2025, doi: 10.25082/aere.2025.01.001.

[28] J. Ominyi, U. Eze, D. Agom, A. Alabi, and A. Nwedu, “Implementing evidence-based practice in critical care nursing: An ethnographic case study of knowledge use,” *J. Adv. Nurs.*, vol. 82, pp. 2407–2426, 2026, doi: 10.1111/jan.70054.

[29] J. Forsberg, C. T. Rasmussen, F. W. J. van den Berg, S. B. Engelsen, and V. Aru, “Fermentation Analytical Technology (FAT): Monitoring industrial E. coli fermentations using absolute quantitative 1H NMR spectroscopy,” *Anal. Chim. Acta*, vol. 1311, no. 342722 Contents, pp. 1–10, 2024, doi: 10.1016/j.aca.2024.342722.

[30] C. S. Yee *et al.*, “Smart fermentation technologies: Microbial process control in traditional fermented foods,” *Fermentation*, vol. 11, no. 6, pp. 1–38, 2025, doi: 10.3390/fermentation11060323.

[31] M. E. Jimenez, C. M. O’Donovan, M. F. de Ullivarri, and P. D. Cotter, “Microorganisms present in artisanal fermented food from South America,” *Front. Microbiol.*, vol. 13, no. September, pp. 1–18, 2022, doi: 10.3389/fmicb.2022.941866.

[32] L. S. Guerra, J. M. Cevallos-Cevallos, S. Weckx, and J. Ruales, “Traditional fermented foods from ecuador: A review with a focus on microbial diversity,” *Foods*, vol. 11, no. 13, pp. 1–14, 2022, doi: 10.3390/foods11131854.

[33] S. Schechtel and A. Bongers, “Representing chemistry culture: ethnography’s methodological potential in chemistry education research and practice,” *Chem. Educ. Res. Pract.*, vol. 25, no. 3, pp. 584–593, 2024, doi: 10.1039/D3RP00272A.

[34] E. U. Alum *et al.*, “Metabolomics-driven standardization of herbal medicine: Advances, applications, and sustainability considerations,” *Nat. Prod. Commun.*, vol. 20, no. 8, pp. 1–16, 2025, doi: 10.1177/1934578X251367650.

[35] P. Du, R. Fan, N. Zhang, C. Wu, and Y. Zhang, “Advances in integrated multi-omics analysis for drug-target identification,” *Biomolecules*, vol. 14, no. 6, pp. 1–25, 2024, doi: 10.3390/biom14060692.

[36] A. Morabito, G. De Simone, R. Pastorelli, L. Brunelli, and M. Ferrario, “Algorithms and tools for data-driven omics integration to achieve multilayer biological insights: a narrative review,” *J. Transl. Med.*, vol. 23, no. 1, pp. 1–26, 2025, doi: 10.1186/s12967-025-06446-x.

[37] Y. M. R. Muhammed, F. Minervini, and I. Cavoski, “From ancient fermentations to modern biotechnology: Historical evolution, microbial mechanisms, and the role of natural and commercial starter cultures in shaping organic and sustainable food systems,” *Foods*, vol. 14, no. 24, pp. 1–36, 2025, doi: 10.3390/foods14244240.

[38] V. Tripathi, “Analyzing the role of legal protection for trademarks and geographical indications in preserving cultural heritage and enhancing global trade,” *J. Law Intellect. Prop. Rights*, vol. 1, no. 1, pp. 50–63, 2024, [Online]. Available: www.ciir.in

[39] D. A. Teferi *et al.*, “Tella (Ethiopian traditional beer): brewing, microbiology, nutrition, health implications, byproducts, and challenges,” *Cogent Food Agric.*, vol. 12, no. 1, pp. 1–36, 2026, doi: 10.1080/23311932.2026.2631822.

[40] J. P. Tamang, “Dietary culture and antiquity of the Himalayan fermented foods and alcoholic fermented beverages,” *J. Ethn. Foods*, vol. 9, no. 1, pp. 1–18, 2022, doi: 10.1186/s42779-022-00146-3.

[41] M. Kurtkoti and P. Joshi, “Gender and tribal knowledge systems : Women’s role in preserving indigenous knowledge,” *Young Res.*, vol. 13, no. 1, pp. 20–33, 2024.

[42] L. T. Baniaga, “Challenges and opportunities in integrating indigenous culinary practices into the technology and livelihood education curriculum,” *Stud. Interdiscip. Horizons*, vol. 1, no. 3, pp. 18–27, 2025, doi: 10.64358/z4jvyc05.

[43] L. Liu *et al.*, “The fermentation law of biogenic amines in the pre-fermentation process is revealed by correlation analysis,” *Foods*, vol. 14, no. 4, pp. 1–15, 2025, doi: 10.3390/foods14040583.

[44] W. Wang *et al.*, “Changes in vinegar quality and microbial dynamics during fermentation using a self-designed drum-type bioreactor,” *Front. Nutr.*, vol. 10, no. 1126562, pp. 1–12, 2023, doi: 10.3389/fnut.2023.1126562.

[45] Y. Wang *et al.*, “Visualizing chemical indicators: Spatial and temporal quality formation and distribution during black tea fermentation,” *Food Chem.*, vol. 401, p. 134090, Feb. 2023, doi: 10.1016/j.foodchem.2022.134090.

[46] H. Shi *et al.*, “Dynamic changes in the chemical composition and metabolite profiles of drumstick (Moringa oleifera Lam.) leaf flour during fermentation,” *Lwt*, vol. 155, p. 112973, 2022, doi: 10.1016/j.lwt.2021.112973.

[47] P. Burawat and P. Peamchai, “Investment feasibility analysis for pasteurized bottled fermented fish sauce production in Thailand: perspectives from industry stakeholders,” *Int. J. Syst. Assur. Eng. Manag.*, vol. 16, no. 8, pp. 2767–2784, Aug. 2025, doi: 10.1007/s13198-025-02837-x.

[48] A. Albaiti, L. Narsia, M. Gultom, and F. Deminggus, “The bridge of tradition and learning science : Mapping rthnochemical mental models based on the sasisen and Napnap Mor traditions of the Biak ethnic, Papua, Indonesia,” *J. Cult. Values Educ.*, vol. 9, no. 1, pp. 269–295, 2026, doi: 10.46303/jcve.2026.12 How.

[49] F. J. García-Peñalvo, “Developing robust state-of-the-art reports: Systematic Literature Reviews,” *Educ. Knowl. Soc.*, vol. 23, p. E28600, 2022, doi: 10.14201/eks.28600.

[50] J. He, C. Treude, and D. Lo, “LLM-based multi-agent systems for software engineering: Literature review, vision, and the road ahead,” *ACM Trans. Softw. Eng. Methodol.*, vol. 34, no. 5, pp. 1–30, Jun. 2025, doi: 10.1145/3712003.

[51] S. R. Maji, C. Roy, and S. K. Sinha, “Gas chromatography-mass spectrometry (GC-MS): a comprehensive review of synergistic combinations and their applications in the past two decades,” *J. Anal. Sci. Appl. Biotechnol.*, vol. 5, no. 2, pp. 72–85, 2023, doi: 10.48402/IMIST.PRSM/jasab-v5i2.40209.

[52] Y. He *et al.*, “Characterization of key compounds of organic acids and aroma volatiles in fruits of different actinidia argute resources based on high-performance liquid chromatography (HPLC) and headspace gas chromatography–ion mobility spectrometry (HS-GC-IMS),” *Foods*, vol. 12, no. 19, pp. 1–28, 2023, doi: 10.3390/foods12193615.

[53] V. D. Prokopiou, A. Karampatea, Z. S. Metaxa, and A. V Tsoupras, “Biosensors of wine fermentation for monitoring chemical and biochemical interactions, process indicators and migration of compounds and metabolites , between wine and fermentation vessels — a critical review,” *Biosensors*, vol. 16, no. 153, pp. 1–58, 2026, doi: 10.3390/bios16030153.

[54] D. K. Yadav, K. Chand, and P. Kumari, “Effect of fermentation parameters on physicochemical and sensory properties of Burans wine,” *Syst. Microbiol. Biomanufacturing*, vol. 2, no. 2, pp. 380–392, Apr. 2022, doi: 10.1007/s43393-021-00074-4.

[55] F. G. Nazhira, “Barriers to implementing organic waste-based fermented feed practices among livestock farmers in Kuningan, West Java,” *Livest. Sci. Innov. J.*, vol. 2, no. 2, pp. 66–90, 2025, doi: 10.59261/lsij.v2i2.29.

[56] S. P. Chand, “Methods of Data Collection in Qualitative Research: Interviews, Focus Groups, Observations, and Document Analysis,” *Adv. Educ. Res. Eval.*, vol. 6, no. 1, pp. 303–317, Aug. 2025, doi: 10.25082/AERE.2025.01.001.

[57] C. L. Arntson and M. N. Yoon, “Participant directed mobile interviews: A data collection method for conducting in-situ field research at a distance,” *Int. J. Qual. Methods*, vol. 22, pp. 1–9, 2023, doi: 10.1177/16094069231188254.

[58] D. C. Tura, “Ethnographic qualitative study to explore the sociocultural values, nutritional potential, and health benefits of dabi Teff (Eragrostis Tef) grown in Western Ethiopia,” *Food Sci. Nutr.*, vol. 13, no. 11, pp. 1–13, 2025, doi: 10.1002/fsn3.71130.

[59] M. F. Fiadillah and W. Sumarni, “Science in samin: Reconstructing indigenous knowledge of the samin community into chemical concepts for contextualized education,” *J. Innov. Educ. Cult. Res.*, vol. 7, no. 1, pp. 191–205, 2026, doi: 10.46843/jiecr.v7i1.2593.

[60] B. Chibuye and I. Sen Singh, “Integration of local knowledge in the secondary school chemistry curriculum - A few examples of ethno-chemistry from Zambia,” *Heliyon*, vol. 10, no. 7, pp. 1–15, 2024, doi: 10.1016/j.heliyon.2024.e29174.

[61] M. D. Astuti, H. Hendrawani, and K. Khaeruman, “Integrating Sukarara traditional weaving into chemistry education: Impact on students’ cultural literacy and critical thinking skills,” *Hydrog. J. Kependidikan Kim.*, vol. 14, no. 1, pp. 7–14, 2026, doi: 10.33394/hjkk.v14i1.19331.

[62] A. B. Ndeko *et al.*, “Farmers’ preferred traits, production constraints, and adoption factors of improved maize varieties under South-Kivu rainfed agro-ecologies, eastern D.R. Congo: implications for maize breeding,” *Int. J. Agric. Sustain.*, vol. 23, no. 1, pp. 1–26, 2025, doi: 10.1080/14735903.2025.2464524.

[63] J. R. Bayoï and W. Dieudonné, “Traditional production practices, nutraceutical potential, safety evaluation, and chemometric analysis of furdu sorghum beer: A comprehensive study across dix divisions in far north cameroon,” *Int. J. Food Sci.*, vol. 2026, no. 1, pp. 1–19, Jan. 2026, doi: 10.1155/ijfo/8898315.

[64] M. M. Sooresh, B. P. Willing, and B. C. T. Bourrie, “Opportunities and challenges of understanding community assembly in spontaneous food fermentation,” *Foods*, vol. 12, no. 3, pp. 1–16, 2023, doi: 10.3390/foods12030673.

[65] I. Izquierdo-Bueno, J. Moraga, J. M. Cantoral, M. Carbú, C. Garrido, and V. E. González-Rodríguez, “Smart viniculture: Applying artificial intelligence for improved winemaking and risk management,” *Appl. Sci.*, vol. 14, no. 22, pp. 1–32, 2024, doi: 10.3390/app142210277.

[66] Y. H. Du, M. Y. Wang, L. H. Yang, L. L. Tong, D. S. Guo, and X. J. Ji, “Optimization and scale-up of fermentation processes driven by models,” *Bioengineering*, vol. 9, no. 9, pp. 1–18, 2022, doi: 10.3390/bioengineering9090473.

[67] Z. Yao, T. Xie, H. Deng, S. Xiao, and T. Yang, “Directed evolution of microbial communities in fermented foods: strategies, mechanisms, and challenges,” *Foods*, vol. 14, no. 2, pp. 1–22, 2025, doi: 10.3390/foods14020216.

[68] Q. Du, D. Ye, X. Zang, H. Nan, and Y. Liu, “Effect of low temperature on the shaping of yeast-derived metabolite compositions during wine fermentation,” *Food Res. Int.*, vol. 162, p. 112016, Dec. 2022, doi: 10.1016/j.foodres.2022.112016.

[69] C. X. Thuy *et al.*, “Effect of fermentation conditions (dilution ratio, medium pH, total soluble solids, and saccharomyces cerevisiae yeast ratio) on the ability to ferment cider from tamarillo (solanum betaceum) fruit,” *J. Food Process. Preserv.*, vol. 2024, pp. 1–17, 2024, doi: 10.1155/2024/8841207.

[70] N. Aramrueang, P. Lomwongsopon, S. Boonsong, and P. Kingklao, “Improved spectrophotometric method for determination of high-range volatile fatty acids in mixed acid fermentation of organic residues,” *Fermentation*, vol. 8, no. 5, pp. 1–17, 2022, doi: 10.3390/fermentation8050202.

[71] G. Galarza and J. G. Figueroa, “Volatile compound characterization of coffee (Coffea arabica) processed at different fermentation times using SPME–GC–MS,” *Molecules*, vol. 27, no. 6, pp. 1–15, 2022, doi: 10.3390/molecules27062004.

[72] R. A. R. Rocha *et al.*, “Evaluation of arabica coffee fermentation using machine learning,” *Foods*, vol. 13, no. 3, pp. 1–18, 2024, doi: 10.3390/foods13030454.

[73] J. Sung and J. Cheong, “Quantum medicine: A quantum–mechanical framework for redox biology, disease and precision medicine,” *Clin. Transl. Med.*, vol. 16, no. 1, pp. 1–24, 2026, doi: 10.1002/ctm2.70598.

[74] U. Wyne, “Neuro-spirituality: A brain-based framework for redefining consciousness and spiritual experience,” *Adv. Soc. Sci. Arch. J.*, vol. 5, no. 1, pp. 2255–2265, 2026, [Online]. Available: https://www.preventionweb.net/news/preliminary-report-february-6-2023-earthquakes-turkiye

[75] C. Su, Y. Han, X. Tang, Q. Jiang, T. Wang, and Q. He, “Knowledge-based digital twin system: Using a knowlege-driven

approach for manufacturing process modeling,” *Comput. Ind.*, vol. 159–160, p. 104101, Aug. 2024, doi: 10.1016/j.compind.2024.104101.

[76] P. Brauner *et al.*, “A computer science perspective on digital transformation in production,” *ACM Trans. Internet Things*, vol. 3, no. 2, pp. 1–32, May 2022, doi: 10.1145/3502265.

[77] K. Zhang *et al.*, “Water quality impact on fish behavior: A review from an aquaculture perspective,” *Rev. Aquac.*, vol. 17, no. 1, pp. 1–27, 2025, doi: 10.1111/raq.12985.

[78] X. Tang, C. Lu, P. Meng, and W. Cheng, “Spatiotemporal evolution of the environmental adaptability efficiency of the agricultural system in China,” *Sustain.*, vol. 14, no. 6, pp. 1–15, 2022, doi: 10.3390/su14063685.

[79] Z. T. Al-Sharify *et al.*, “Optimizing beverage production: The role of fluid dynamics in microbial fermentation,” *J. Food Process. Preserv.*, vol. 2025, no. 1, pp. 1–15, 2025, doi: 10.1155/jfpp/8811731.

[80] V. T. Herlina, R. H. B. Setiarto, and I. B. A. Yogeswara, “Unveiling the sociocultural, microbiological, and functional properties of liquid brem, a traditional balinese fermented rice wine: a systematic review,” *J. Ethn. Foods*, vol. 13, no. 4, pp. 1–17, 2026, doi: 10.1186/s42779-026-00305-w.

[81] Y. Liu, L. Luo, and L. Zeng, “Guidelines for sensory evaluation of tea: Traditional chinese method and quantitative descriptive analysis,” *AgriFood J. Agric. Prod. Food*, vol. 1, no. 1, pp. 15–20, 2025, doi: 10.1002/agf2.70001.

[82] M. Y. B. Adjei *et al.*, “Integrative review on the use of sensory evaluation methods in consumer-led product development for indigenous fruits and vegetables,” *Front. Sustain. Food Syst.*, vol. 9, no. January, pp. 1–12, 2026, doi: 10.3389/fsufs.2025.1657001.