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EMERGING TECHNOLOGIES FOR THE UTILIZATION OF FRUIT WASTE IN THE FORMULATION AND PRODUCTION OF BEVERAGES – A SYSTEMATIC REVIEW OF THE LITERATURE

TECNOLOGIAS EMERGENTES PARA O APROVEITAMENTO DE RESÍDUOS DE FRUTAS NA FORMULAÇÃO E PRODUÇÃO DE BEBIDAS – UMA REVISÃO SISTEMÁTICA DA LITERATURA

TECNOLOGÍAS EMERGENTES PARA LA UTILIZACIÓN DE RESIDUOS DE FRUTAS EN LA FORMULACIÓN Y PRODUCCIÓN DE BEBIDAS: UNA REVISIÓN SISTEMÁTICA DE LA LITERATURA

João Guilherme Sodré de Souza
Undergraduate in Chemical Processes Technology, Federal Institute of Education, Science and Technology of Maranhão (IFMA) – São Luís Campus – Monte Castelo, Brazil
E-mail: souza.guilherme@acad.ifma.edu.br

Miguel Vitor Lima Costa
Undergraduate in Chemical Processes Technology, IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: miguelc@acad.ifma.edu.br

Douglas Souza Maciel
Undergraduate in Chemical Processes Technology, IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: douglassouza@acad.ifma.edu.br

Pedro Henrique Arruda Chaves
Undergraduate in Chemical Processes Technology, IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: arrudachaves@acad.ifma.edu.br

Mirella Teles Oliveira
Undergraduate in Chemical Processes Technology, IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: mirella.oliveira@acad.ifma.edu.br

Matheus Filipe Leitão de Oliveira
PhD Student, Graduate Program in Chemistry - IFMA – São Luís Campus – Monte Castelo, Brazil

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E-mail: matteusfilipe@outlook.com

Jeiza Freitas Pinheiro
PhD Student, Graduate Program in Chemistry, IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: jeizafreitaspi@gmail.com

Adriana Silva Caldas
PhD Student, Graduate Program in Chemistry, IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: caldas.adriana08@gmail.com

Luiz Carlos Rocha Junior
PhD Student, Graduate Program in Chemistry, IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: luizcarlos@ifma.edu.br

Arlan Silva Freitas
PhD in Animal Science, Academic Department of Chemistry
IFMA – São Luís Campus – Monte Castelo, Brazil
E-mail: arlan@ifma.edu.br

Abstract

This systematic literature review aimed to critically evaluate the use of fruit agro-industrial residues in the production of alcoholic beverages, with emphasis on technological performance, functional properties, and sustainability. Nineteen studies published between 2016 and 2025 were analyzed, considering residue types, processing conditions, physicochemical characteristics, sensory acceptance, and industrial application potential. The results indicate that peels, pomace, and seeds are viable substrates for producing beers, wines, and liqueurs due to their content of fermentable sugars and high concentrations of phenolic compounds, flavonoids, and anthocyanins, which contribute to antioxidant activity, oxidative stability, and sensory complexity. In several cases, beverages produced from residues showed higher total phenolic contents than conventional products. However, the evidence reveals significant methodological heterogeneity, with variations in fermentation parameters, extraction techniques, and sensory analysis protocols. Most studies were conducted at laboratory scale, limiting extrapolation to industrial contexts. Conventional processes such as fermentation and maceration still predominate, while emerging approaches focused on process optimization show potential to improve efficiency and standardization. Sensory acceptance is generally favorable but often based on small panels of untrained consumers. In addition, safety and regulatory aspects remain underexplored. From a sustainability perspective, residue valorization aligns with circular economy principles. Nevertheless, challenges persist regarding raw material variability, process standardization, and large-scale feasibility, indicating the need for further studies to support industrial application.

Keywords: Bioconversion; Phenolic compounds; Alcoholic fermentation; Circular economy; Fruit residue valorization.

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Resumo

Esta revisão sistemática da literatura teve como objetivo avaliar criticamente o uso de resíduos agroindustriais de frutas na produção de bebidas alcoólicas, com ênfase no desempenho tecnológico, propriedades funcionais e sustentabilidade. Foram analisados 19 estudos publicados entre 2016 e 2025, considerando tipos de resíduos, condições de processamento, características físico-químicas, aceitação sensorial e potencial de aplicação industrial. Os resultados indicam que cascas, bagaços e sementes constituem substratos viáveis para a produção de cervejas, vinhos e licores, devido ao seu conteúdo de açúcares fermentescíveis e elevada concentração de compostos fenólicos, flavonoides e antocianinas, os quais contribuem para a atividade antioxidante, estabilidade oxidativa e complexidade sensorial das bebidas. Em diversos casos, bebidas elaboradas a partir de resíduos apresentaram maiores teores de fenólicos totais em comparação aos produtos convencionais. Contudo, as evidências revelam significativa heterogeneidade metodológica, com variações nos parâmetros fermentativos, técnicas de extração e protocolos de análise sensorial. A maioria dos estudos foi conduzida em escala laboratorial, o que limita a extrapolação dos resultados para o contexto industrial. Processos convencionais, como fermentação e maceração, ainda predominam, enquanto abordagens emergentes voltadas à otimização de processos demonstram potencial para melhorar a eficiência e a padronização. A aceitação sensorial é, em geral, favorável, porém frequentemente baseada em painéis reduzidos de consumidores não treinados. Além disso, aspectos relacionados à segurança e à regulamentação permanecem pouco explorados. Sob a perspectiva da sustentabilidade, a valorização de resíduos está alinhada aos princípios da economia circular. Entretanto, persistem desafios quanto à variabilidade das matérias-primas, padronização dos processos e viabilidade em larga escala, indicando a necessidade de estudos adicionais para aplicação industrial.

Palavras-chave: Bioconversão; Compostos fenólicos; Fermentação alcoólica; Economia circular; Valorização de resíduos de frutas.

Resumen

Esta revisión sistemática de la literatura tuvo como objetivo evaluar críticamente el uso de residuos agroindustriales de frutas en la producción de bebidas alcohólicas, con énfasis en el desempeño tecnológico, las propiedades funcionales y la sostenibilidad. Se analizaron diecinueve estudios publicados entre 2016 y 2025, considerando tipos de residuos, condiciones de procesamiento, características fisicoquímicas, aceptación sensorial y potencial de aplicación industrial. Los resultados indican que cáscaras, bagazos y semillas constituyen sustratos viables para la producción de cervezas, vinos y licores debido a su contenido de azúcares fermentables y a las altas concentraciones de compuestos fenólicos, flavonoides y antocianinas, los cuales contribuyen a la actividad antioxidante, la estabilidad oxidativa y la complejidad sensorial. En varios casos, las bebidas elaboradas a partir de residuos presentaron mayores contenidos de fenólicos totales en comparación con productos convencionales. Sin embargo, la evidencia muestra una significativa heterogeneidad metodológica, con variaciones en los parámetros de fermentación, técnicas de extracción y protocolos de análisis sensorial. La mayoría de los estudios se realizó a escala de laboratorio, lo que limita la extrapolación a contextos industriales. Los procesos convencionales como la fermentación y la maceración aún predominan, mientras que enfoques emergentes orientados a la optimización de procesos muestran potencial para mejorar la eficiencia y la estandarización. La aceptación sensorial es generalmente favorable, pero suele basarse en paneles pequeños de consumidores no entrenados. Además, los aspectos de seguridad y regulación permanecen poco explorados. Desde la perspectiva de la sostenibilidad, la valorización de residuos se alinea con los principios de la economía circular. No obstante, persisten desafíos relacionados con la variabilidad de la materia prima, la estandarización de los procesos y la viabilidad a gran escala, lo que indica la necesidad de más estudios para su aplicación industrial.

Palabras clave: Bioconversión; Compuestos fenólicos; Fermentación alcohólica; Economía circular; Valorización de residuos de fruta

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1. Introduction

The growing global demand for differentiated alcoholic beverages has driven the search for alternative raw materials capable of adding sensory, functional, and economic value to products. Within this context, the use of fruit residues has emerged as a promising strategy to reduce waste and expand the portfolio of fermented and distilled beverages. In this study, the term 'fruit residues' is adopted as the primary designation for materials generated during fruit processing, including peels, seeds, pomace, and discarded pulp. Although the terms 'by-products' and 'co-products' appear in the literature, they are not used interchangeably here in order to ensure conceptual consistency throughout the analysis. The term "emerging technologies" refers to the application of conventional processing techniques (fermentation, maceration, distillation) to novel substrates (fruit residues), as well as the optimization of these processes through response surface methodology and other statistical tools to maximize yield and functional quality.

Studies such as those by Okonkwo and Dilar (2016), Silva et al. (2017), Feitosa et al. (2020), and Salas-Millán et al. (2022) demonstrate that by-products such as peels, seeds, peduncles, and residual pulps present a composition rich in bioactive compounds, vitamins, and fermentable sugars, favoring their use in fermentation processes. The production of cream-type liqueurs from residues of acerola, mango, guava, and soursop highlights the potential of these materials in the creation of new alcoholic products with high acceptability rates (Feitosa et al., 2020). Similarly, Okonkwo and Dilar (2016) demonstrated the feasibility of producing wine from pineapple peels, emphasizing the sustainability of this practice. This diversification is also evident in the production of specialty beers, a segment that has grown significantly in Brazil. Research on beers formulated with guaraná peel indicates that the inclusion of this residue alters attributes such as color, bitterness, and aromatic profile, while also showing high sensory acceptance (Farias et al., 2020; Alves et al., 2021). In addition to guaraná, residues such as cashew peduncle and orange peels have been used to develop beers with higher polyphenol content and antioxidant activity (Pereira et al., 2020).

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The use of fruit parts that are typically discarded has proven effective for the nutritional and functional enrichment of different fermented beverages. Grape peel, for example, frequently separated during industrial processing, showed significant performance when incorporated into the production of fermented beverages, increasing the content of phenolic compounds and antioxidant activity (Coutinho et al., 2024). This behavior highlights the ability of these materials to provide valuable substrates, also observed in alcoholic formulations developed with non-conventional fruit parts (Balamaze; Wambete, 2017; Méndez et al., 2022). Among the materials with the greatest potential, those derived from citrus fruits stand out, whose industrial processing generates expressive volumes of external structures such as peels. Research involving the fermentation of tea-wine produced from these parts demonstrated the presence of flavonoids, organic acids, and essential oils capable of intensifying aroma and enhancing the antioxidant activity of the final beverage (Liu et al., 2025). These results are consistent with those obtained in beer formulations containing orange peel, which showed a clear sensory impact and enriched composition (Pereira et al., 2020).

The use of fruit residues such as citrus peels in liquor production has also been explored as an alternative to add value to industrial waste. Studies have shown that maceration of orange peels in hydroalcoholic solutions can produce beverages with high phenolic content and aromatic complexity, characterized by monoterpenes and sesquiterpenes (Navarro-Martínez et al., 2019). Furthermore, sour cherry pomace from the liquor industry has been identified as a rich source of phenolic compounds, including cyanidin-3-O-glucoside, catechin, and epicatechin, which remain in the residue after processing and can be recovered for use in functional products (Maurício et al., 2020). Similarly, the use of jabuticaba residues in beer production has demonstrated that the addition of the whole fruit or its fractions can significantly increase total acidity, soluble solids, and alcohol content, as well as improve sensory attributes such as color and flavor stability (Santos et al., 2021).

Given the diversity of available fruits and the significant volume of residues generated by agro-industry, it becomes essential to systematize scientific

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knowledge related to the conversion of these residues into innovative alcoholic beverages. Thus, this study aims to carry out a systematic literature review, gathering evidence on technological, fermentative, and sensory strategies applied to the use of fruit residues in the formulation and production of alcoholic beverages, highlighting trends, challenges, and future potential in the field of sustainable beverages.

2. Methodology

The systematic review was conducted following a carefully structured methodological framework to ensure rigor, transparency, and reproducibility. This approach was selected due to its ability to systematically identify, evaluate, and synthesize available evidence regarding the use of fruit residues in the formulation and production of alcoholic beverages, a topic that has gained increasing relevance within the context of sustainable practices and technological innovation in the food and beverage sector.

2.1 Problem Identification and Research Question

The research problem was defined based on the observation that, despite the extensive generation of fruit residues in agro-industrial and domestic processing, significant gaps remain regarding their technological application in alcoholic beverage production. A substantial proportion of these residues exhibits nutritional and bioactive characteristics favorable for fermentation, yet remains underutilized. Accordingly, the following guiding research question was established:

What recent scientific evidence addresses the use of fruit residues in the production of alcoholic beverages, and which technological and functional attributes are associated with this process?

This question guided all stages of the review.

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2.2 Literature Search Strategy

A systematic search was performed in 2025, in the databases Google Scholar, SciELO, Scopus, and CAPES Periodicals. The following search strings were used for each database:

- **Google Scholar:** ("fruit residues" AND "alcoholic beverages") OR ("fruit peel" AND "wine") OR ("fruit by-product" AND "beer");
- **SciELO:** ("fruit residues" AND "alcoholic beverages") [English] OR ("resíduos de frutas" AND "bebidas alcoólicas") [Portuguese] OR ("residuos de frutas" AND "bebidas alcohólicas") [Spanish]
- **Scopus:** TITLE-ABS-KEY (("fruit residue*" OR "fruit peel*" OR "fruit by-product*") AND ("alcoholic beverage*" OR "wine" OR "beer" OR "liquor" OR "spirit"))
- **CAPES Periodicals:** ("fruit residues" AND "alcoholic beverages") OR ("fruit peel" AND "fermentation")

Publications from 2016 to 2025 were considered. The search was limited to peer-reviewed articles, excluding reviews, conference proceedings, book chapters, theses, and dissertations. The detailed search strategy and results are presented in Table 1.

Table 1 – Detailed search strategy per database.

Database	Search String	Filters	Records found
Google Scholar	("fruit residues" AND "alcoholic beverages") OR ("fruit peel" AND "wine")	Since 2016, peer-reviewed articles	210
SciELO	("fruit residues" AND "alcoholic beverages") OR ("resíduos de frutas" AND "bebidas alcoólicas")	Since 2016	45
Scopus	TITLE-ABS-KEY(("fruit residue* OR *"fruit peel*") AND ("alcoholic beverage*" OR "wine"))	PUBYEAR ≥ 2016, article	120
CAPES Periodicals	("fruit residues" AND "alcoholic beverages")	Since 2016	50
Total			**425**

Source: Prepared by the authors (2026).

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2.3 Inclusion and Exclusion Criteria

Studies were included if they: (i) exclusively addressed the use of fruit residues or by-products in alcoholic beverage production; (ii) presented an experimental design with a clear description of fermentation, processing, or product characterization methods; (iii) were fully accessible as full-text articles; (iv) were published between 2016 and 2025; and (v) corresponded to indexed peer-reviewed scientific articles.

Studies were excluded if they: (i) were not directly related to the research topic; (ii) consisted of non-peer-reviewed academic documents (theses, dissertations, monographs, abstracts, conference proceedings, book chapters); (iii) were duplicates; (iv) were incomplete, illegible, or inaccessible; (v) addressed non-alcoholic beverages or residues outside the scope of this review (e.g., non-fruit residues, non-beverage applications); or (vi) were review articles or meta-analyses.

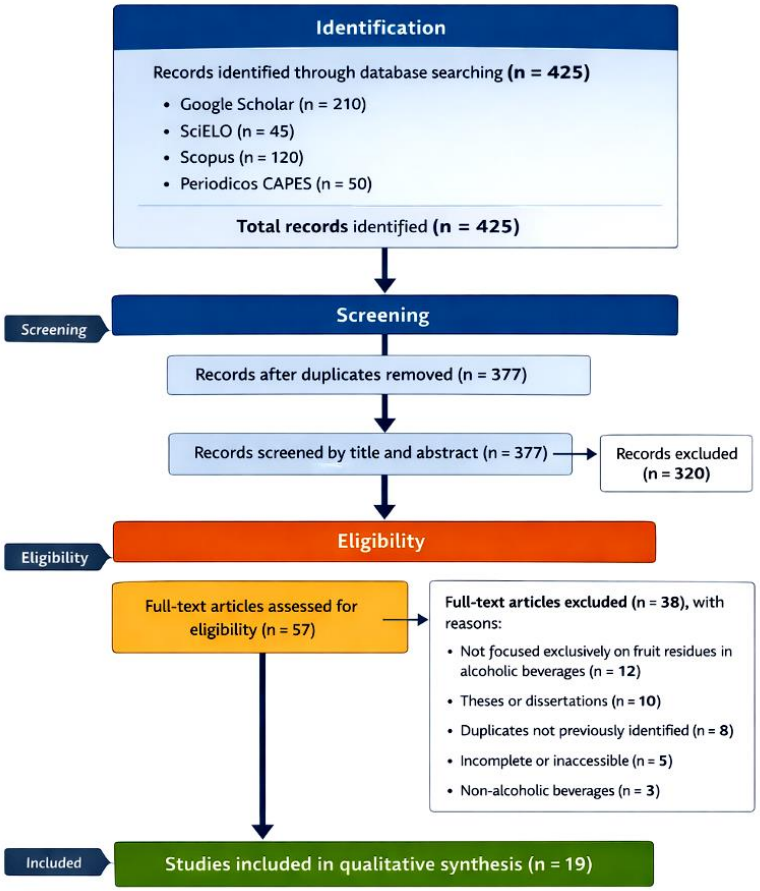
2.4 Screening and Study Selection

The retrieved records (n=425) were exported to a reference manager, and duplicates (n=48) were removed, resulting in 377 unique records. Titles and abstracts were screened against the inclusion criteria, excluding 320 records. The remaining 57 full-text articles were retrieved and assessed for eligibility. Of these, 38 were excluded: 12 for not focusing exclusively on fruit residues in alcoholic beverages, 10 for being theses or dissertations, 8 for being duplicates not previously identified, 5 for being incomplete or inaccessible, and 3 for addressing non-alcoholic beverages. At the end of this systematic process, 19 studies were selected and included in the final review. Figure 1 presents the PRISMA flowchart.

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Figure 1 – PRISMA flowchart of the study selection process.



Source: Prepared by the authors (2026).

2.5 Data Extraction and Categorization

The selected studies were organized into a structured data extraction matrix, including information on authors, publication year, type of residue used, type of beverage produced, study objectives, methodological procedures, fermentation conditions (temperature, time, yeast strain), and main findings (physicochemical parameters, sensory scores, bioactive compound concentrations). This matrix served as the basis for comparative analysis.

2.6 Quality Assessment and Heterogeneity Analysis

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A critical appraisal of the methodological quality of the 19 included studies was performed using an adapted checklist based on the Joanna Briggs Institute (JBI) criteria for experimental studies. Each study was evaluated for: (i) clarity of objectives; (ii) appropriateness of experimental design; (iii) detailed description of fermentation conditions (temperature, pH, time, yeast type); (iv) use of appropriate controls; (v) replication of experiments; (vi) statistical analysis; and (vii) presentation of results with measures of variability.

The assessment revealed substantial heterogeneity. Twelve studies (63%) presented robust methodologies with clear descriptions, appropriate controls, and statistical validation. Seven studies (37%) showed limitations, including insufficient detail on fermentation parameters (e.g., lack of temperature control or yeast concentration), absence of replication, or incomplete presentation of results. This heterogeneity was considered when interpreting findings, giving greater weight to methodologically stronger studies. No study was excluded solely on quality grounds, but limitations were noted in the discussion.

2.7 Data Synthesis and Analysis

Data synthesis was performed according to the principles of a systematic literature review, emphasizing the critical comparison of similarities, divergences, and recurring patterns among the selected studies. A narrative synthesis was conducted and structured by beverage type (wines, beers, liqueurs, and distilled beverages) and by thematic categories, including biotechnological potential, processing technologies, sensory characterization, and sustainability. Owing to the heterogeneity of the experimental designs, residue types, analytical methods, and reported outcomes, a quantitative synthesis by meta-analysis was not feasible.

2.8 Limitations of the Review Methodology

This review has several methodological limitations. First, the exclusion of gray literature (theses, dissertations, conference proceedings) may have introduced

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publication bias, as studies with non-significant results are less likely to be published in peer-reviewed journals. Second, the search was limited to four databases and may have missed relevant studies indexed elsewhere. Third, the heterogeneity of the included studies precluded quantitative synthesis. Fourth, no validated quality assessment tool specifically designed for food technology reviews was available, although an adapted JBI checklist was used. These limitations are further discussed in Section 4.8.

3. Results

The systematization of the selected studies provides an integrated overview of the main approaches employed in the utilization of agro-industrial fruit residues for the production of alcoholic beverages. Table 2 presents, in an organized and chronological manner, the evidence available in the literature, encompassing the types of residues used, the methodologies applied, and the main results obtained across different beverage matrices. Only studies that fully met the inclusion criteria are presented.

Table 2 – Summary of studies on the utilization of agro-industrial fruit residues in the production of alcoholic beverages and their technological applications, including the type of residue and beverage, methodologies employed, main results, and conclusions, organized chronologically.

Authors/Year	Type of Residue / Beverage	Key Methodological Features	Main Results	Conclusion
Okonkwo; Dilar (2016)	Pineapple peel / Wine	Fermentation with *S. cerevisiae*; 5 days; 28±1°C	pH 4.82-5.32; alcohol 0.26-0.68%	Residue is a viable fermentative substrate
Silva et al. (2016)	Orange peel, albedo, seeds / Various	Chemical characterization; proximate analysis	Carbohydrates 66.9-78.2%; pectin 5.6-8.0%	Residues have multiple biotechnological applications
Balamaze; Wambete (2017)	Pineapple and mango peels / Wine	Fermentation 6 months; TSS 24-32°Brix initial	Final TSS 10.1-14.5°Brix; alcohol 12-18%	Peel is an efficient carbon source
Silva et al. (2017)	Tangerine peel / Liqueur	Alcoholic maceration 30	pH 6.04-6.35; total sugars 28.4-	Feasible for liqueur

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		days; 27°C; 38% alcohol	35.0%; alcohol 25.6-30.8%	production
Nascimento et al. (2018)	Jabuticaba peel syrup / Wine	Fermentation 30°C; Monod kinetic modeling	ΔS 152.3 $g.L^{-1}$; ΔP 93.7 $g.L^{-1}$; YP/S 0.615	Monod model adequately describes fermentation
Navarro-Martínez et al. (2019)	Citrus peels (3 cultivars) / Liqueur	Maceration 3 months; 60% alcohol; adjusted to 30%	TPC 446-557 mg $GAE.mL^{-1}$; ABTS 3.88-4.77 mmol $Trolox.mL^{-1}$	High aromatic potential; cultivar-dependent
Farias et al. (2020)	Guaraná peel (10-40%) / Beer	Descriptive sensory analysis; TI and TDS tests	Sensory scores 6.6-7.2; increased bitterness with concentration	Direct impact on sensory quality; 30% best acceptance
Maurício et al. (2020)	Sour cherry pomace / Extracts	Decoction (100°C) vs. maceration (25°C); HPLC analysis	TPC: decoction 289 mg $GAE.100g^{-1}$; maceration 31-40 mg	Method influences yield; decoction more efficient
Pereira et al. (2020)	Cashew peduncle (5-10%) + orange peel (0.6%) / Wheat beer	Fermentation 15 days at 13°C; 6 formulations	Polyphenols 516-727 mg $GAE.L^{-1}$; ABTS 1568-1737 $\mu M.L^{-1}$	Synergistic effect between residues
Feitosa et al. (2020)	Acerola, pineapple, mango, guava, soursop residues / Cream liqueur	Maceration 20 days; heat treatment 60°C/2h	Alcohol 15.1-31.1%; total sugars 52.8-65.1%; pH 6.1-6.6	All formulations met legal standards; acceptance >70%
Alves et al. (2021)	Guaraná peel / Pilsner beer	Addition at 0%, 10%, 20%, 30%, 40%; sensory evaluation	Alcohol: control 5.78%, T2 2.36%; color increased from 4.2 to 12.3 EBC	Concentration affects acceptance; 74% purchase intent for T2
Santos et al. (2021)	Jabuticaba (fermentation vs. maturation) + bread flour / Fruit Beer Ale	Fermentation 7 days; maturation 15 days at 5°C	Alcohol: control 5.87%, maturation 5.24%; color 57-75 EBC	Maturation addition gave best overall impression (7.14/9)
Suthovski et al. (2021)	Pecan shell extract (5%, 10%, 15%) / Oatmeal Stout	Extract added at bottling; physicochemical and antioxidant analysis	Alcohol 5.0%; pH 4.25-4.49; antioxidant activity 3.38-3.51 $mmol.L^{-1}$	Adds functional value; good sensory acceptance
Méndez et al. (2022)	Apple, pear, peach peels (25-75%) / Fermented beverage	Fermentation 7 days; 3 formulations	Color and aroma varied with peel concentration; best acceptance at 75% peel	Formulation influences quality; market-competitive

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Salas-Millán et al. (2022)	Melon peels (2 cultivars) / Wine	Fermentation 15°C; *S. cerevisiae*; GC-MS analysis	Alcohol ~10%; ethyl hexanoate OAV 19.6-50.7	Relevant sensory potential; Okashi preferred (82.8/100)
Li et al. (2023)	Green banana peel and pulp / Wine	Fermentation with pectinase; HPLC analysis	TPC 894.9 mg GAE.L^{-1}; antioxidant activity 24.9%	Combined use of peel and pulp improves quality
Dutra et al. (2023)	Pineapple peel (0-100% substitution) / Mixed alcoholic beverage	5 formulations; 8% target alcohol	pH 3.94-4.03; alcohol ~8%; color differences minimal up to 75% substitution	Technological feasibility; 70% purchase intent
Coutinho et al. (2024)	Blueberry, jabuticaba, grape, pineapple peels / Fermented beverages	Fermentation 28°C; S. cerevisiae; kinetic modeling	TPC 781-1597 mg GAE.L^{-1}; antioxidant activity 24.9-69.0%	High functional potential; jabuticaba peel best overall
Liu et al. (2025)	Orange peel / Fermented tea-wine	Response surface optimization; 26 flavor compounds identified	TPC 2.32 mg.mL^{-1}; DPPH 90.8%; alcohol 12.5%	High antioxidant capacity; optimized conditions established

Source: Prepared by the authors (2026).

The compiled data demonstrate that fruit residues, particularly peels, pomace, and other fruit residues, exhibit high technological versatility, functioning as fermentable substrates, sources of bioactive compounds, and modifiers of sensory properties. The results consistently indicate the maintenance or improvement of physicochemical parameters, as well as an increase in antioxidant activity across various formulations, reinforcing the potential of these materials in the production of value-added alcoholic beverages. Based on this evidence, it is pertinent to further deepen the critical analysis of these findings, considering the technological, functional, and sustainability aspects involved, as discussed in the following section.

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4. Discussion

4.1 Biotechnological Potential and Composition of Fruit Residues

The analysis of the selected studies confirms that fruit residues, defined as peels, pomace, seeds, and discarded pulps, exhibit high biotechnological potential due to their chemical composition rich in bioactive compounds. Investigations involving grape, jabuticaba, pineapple, and blueberry peels have demonstrated significant concentrations of phenolic compounds and high antioxidant activity, characteristics that contribute to the functionality and stability of fermented beverages (Navarro-Martínez et al., 2019; Coutinho et al., 2024). Residues derived from the liqueur industry, such as sour cherry pomace, also present high levels of polyphenols, flavonoids, and anthocyanins, compounds associated with both antioxidant activity and the sensory properties of final products (Maurício et al., 2020).

The distribution of these bioactive compounds across different parts of the fruit reveals that peels concentrate the largest fraction of secondary metabolites. Studies on citrus residues demonstrate that peels contain higher levels of phenolic compounds and aromatic compounds compared to juice, reinforcing their relevance in the formulation of alcoholic beverages (Silva et al., 2016; Navarro-Martínez et al., 2019). Salas-Millán et al. (2022) and Li et al. (2023) obtained similar results with banana and melon, in which both the peel and the whole fruit contributed to the chemical composition of fermented beverages. Fruit residues also present suitable composition for fermentation processes, mainly due to the presence of fermentable sugars. Studies demonstrate that pineapple peels, jabuticaba residues, and seasonal fruit residues can be used as efficient substrates for alcoholic fermentation (Balamaze; Wambete, 2017; Méndez et al., 2022). According to Nascimento et al. (2018) and Dutra et al. (2023), partial substitution of pulp by peel does not compromise relevant physicochemical parameters.

The characterization of wines and liqueurs produced from by-products demonstrates the presence of volatile compounds such as higher alcohols, esters,

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and terpenes, responsible for complex sensory attributes (Navarro-Martínez et al., 2019; Salas-Millán et al., 2022). In fermented beverages from citrus residues, flavonoids and natural aromatic compounds contribute to aroma, flavor, and color, increasing consumer acceptance (Suthovski et al., 2021; Liu et al., 2025). Even after extraction of bioactive compounds, the remaining residues still present significant energetic value and can be used as energy sources (Silva et al., 2016; Maurício et al., 2020), reinforcing their role in circular economy models.

Despite the promising results reported across the literature, the technological performance of fruit residues does not occur uniformly across studies, being strongly dependent on the experimental conditions employed. In fermentation systems using pineapple and mango peels, for instance, high fermentation efficiency and satisfactory alcohol production have been reported; however, these outcomes were achieved under controlled laboratory conditions, including prior adjustments of soluble solids and pH, which limits their direct extrapolation to industrial contexts (Okonkwo; Dilar, 2016; Balamaze; Wambete, 2017).

Similarly, fermented beverages produced from jabuticaba and blueberry residues have demonstrated technological feasibility, yet with considerable variation in kinetic and biochemical parameters, reflecting significant methodological heterogeneity (Nascimento et al., 2018; Coutinho et al., 2024). In this sense, although fruit residues exhibit substantial technological potential, these findings should be interpreted with caution, as most available evidence is derived from laboratory-scale experiments conducted under heterogeneous methodological frameworks, highlighting the need for process standardization and validation under real production conditions.

4.2 Emerging Processing and Extraction Technologies Applied to Residues

The analyzed studies demonstrate that alcoholic fermentation applied to fruit residues has shown consistent technological performance under laboratory conditions. In wine production from fruit peels, musts adjusted between 24 and 32 °Brix showed a significant reduction in soluble solids during fermentation, reaching

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values between 10.1 and 14.5 °Brix, with alcohol contents ranging from 12 to 18% (v/v) (Balamaze; Wambete, 2017; Coutinho et al., 2024). Nascimento et al. (2018) and Dutra et al. (2023) report that fruit residues contain sufficient fermentable sugars to sustain microbial activity.

Within the scope of this review, it is essential to clearly distinguish between conventional and emerging technologies, as this distinction directly influences the interpretation of the reported findings. Conventional approaches, such as alcoholic fermentation, maceration, and liqueur formulation, are well-established and widely applied, typically with minor procedural variations across studies (Silva et al., 2017; Navarro-Martínez et al., 2019). In contrast, emerging technologies, including response surface optimization, kinetic modeling of fermentation, and advanced analytical techniques such as GC–MS, offer enhanced process control, improved reproducibility, and deeper insights into the biochemical transformations involved (Salas-Millán et al., 2022; Liu et al., 2025). Therefore, although conventional processes still predominate in most analyzed studies, emerging approaches represent a critical advancement toward process optimization, product standardization, and industrial scalability.

On the other hand, the application of these emerging technologies in experimental studies has demonstrated practical advantages, particularly in optimizing fermentation conditions and enhancing the recovery of bioactive compounds. For instance, response surface methodology has been effectively employed to define optimal process parameters, while advanced analytical techniques such as GC–MS have enabled a more detailed characterization of volatile profiles. These approaches contribute not only to process efficiency but also to improved product differentiation and quality consistency under controlled conditions (Salas-Millán et al., 2022; Liu et al., 2025).

The influence of process variables on fermentation efficiency has been widely investigated. In studies involving orange peel wine with tea, optimization by response surface methodology indicated ideal conditions: substrate ratio 1:3 (orange peel:tea), yeast 4.9%, temperature 29°C, fermentation time 7 days, resulting in phenolic compounds of 2.32 $mg \cdot mL^{-1}$ and DPPH scavenging of

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approximately 90.8% (Liu et al., 2025). These data reinforce that controlling operational conditions is crucial to maximize functional quality.

Regarding extraction technologies, different approaches have been used. In sour cherry pomace, decoction at 100°C showed higher yields of phenolic compounds (up to 289 mg GAE·100 g^{-1}), while maceration at 25°C offered advantages in preserving sensitive compounds and reducing energy consumption (Navarro-Martínez et al., 2019; Maurício et al., 2020). In citrus liqueur production, prolonged alcoholic maceration (3 months) favored the efficient extraction of terpenes, resulting in beverages with complex aromatic profiles (Navarro-Martínez et al., 2019). However, most of these processes have only been tested at laboratory or pilot scale, and industrial-scale validation remains lacking.

4.3 Application of Fruit Residues and Plant Extracts in Craft and Specialty Beer Production

The incorporation of fruit residues into craft beers has been explored as a strategy for product diversification. The use of by-products such as peels and plant extracts introduces new chemical compounds into the beer matrix, influencing physicochemical and sensory attributes (Alves et al., 2021; Suthovski et al., 2021). The addition of aqueous pecan shell extract during bottling allowed the preservation of phenolic compounds without compromising overall sensory acceptance, although higher concentrations (5%) reduced flavor and color scores (Suthovski et al., 2021).

The use of guaraná peel in pilsner beers showed that higher concentrations resulted in increased residual bitterness and darker color, negatively affecting sensory acceptance (Farias et al., 2020; Alves et al., 2021). Pereira et al. (2020) reported that the addition of cashew peduncle and orange peel at 5% and 10% in wheat beers resulted in changes in fermentation kinetics and increased polyphenol content proportionally to residue concentration, with synergistic effects between residues. The use of apple, pear, and peach peels also showed sensory variations associated with plant material concentration, with formulations containing higher

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peel content exhibiting greater sweetness and sensory complexity (Méndez et al., 2022).

The addition of jabuticaba fruit to beer formulations significantly altered the physicochemical profile. Santos et al. (2021) demonstrated that beers with jabuticaba added during maturation presented higher total acidity (0.31% m/v) and soluble solids (15.66 °Brix) compared to the control, and received the highest scores for overall impression (7.14 on a 9-point scale). These findings indicate that both residue type and addition timing are critical for consumer acceptance. However, all studies were conducted at laboratory or pilot scale (typically 5-20 L batches), and sensory panels were limited (12-100 untrained consumers), which limits the generalizability of acceptance claims.

4.4 Development of Alcoholic Liqueurs from Agro-Industrial Fruit Residues

The production of liqueurs from fruit residues has emerged as a viable technological alternative. Studies with citrus residues have demonstrated that alcoholic maceration enables the production of liqueurs with high phenolic content and aromatic profiles characterized by monoterpenes and sesquiterpenes (Navarro-Martínez et al., 2019; Maurício et al., 2020). Maceration of approximately 50 g of peel in 60% v/v hydroalcoholic solution, followed by adjustment to 30% alcohol and 20°Brix, resulted in beverages with balanced sensory characteristics (Silva et al., 2017; Navarro-Martínez et al., 2019).

Although alcoholic maceration is consistently reported as an effective technique for extracting bioactive compounds from fruit residues, the efficiency of this process varies substantially depending on solvent composition, extraction time, and residue characteristics. Studies using citrus peels have demonstrated that hydroalcoholic solutions with ethanol concentrations between 50% and 70% (v/v) enhance the solubilization of both polar and non-polar compounds, including phenolics and terpenes, thereby contributing to more complex aromatic profiles (Navarro-Martínez et al., 2019; Maurício et al., 2020). In contrast, lower ethanol concentrations tend to favor the extraction of hydrophilic compounds but may limit

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the recovery of volatile aromatic fractions. This variability highlights that extraction efficiency is not solely dependent on the raw material, but rather on the interaction between solvent polarity and the chemical composition of the residues, reinforcing the need for optimized and standardized extraction protocols.

Feitosa et al. (2020) produced cream-type liqueurs from residues of acerola, pineapple, mango, guava, and soursop. All formulations met Brazilian legal standards for alcoholic beverages (alcohol content 15.1-31.1%; total sugars 52.8-65.1%) and showed good sensory acceptance, with acceptability indices above 70% for most formulations. The liqueurs also presented high anthocyanin content (up to 5.38 $mg.100g^{-1}$ in mango liqueur) and flavonoid content (up to 40.72 $mg.100g^{-1}$ in acerola liqueur). Color degradation kinetics followed zero-order models, with guava liqueur showing the best stability. These results suggest that liqueur production from residues is technologically feasible and economically promising for small-scale producers.

In addition to extraction conditions, formulation parameters such as sugar concentration, alcohol content, and thermal treatment play a critical role in determining the physicochemical stability and sensory acceptance of liqueurs. Higher sugar concentrations contribute to increased viscosity and sweetness perception, which may enhance consumer acceptance but also influence microbial stability and shelf life. Similarly, alcohol content affects not only preservation but also the perception of aroma and flavor compounds, acting as a carrier for volatile molecules (Silva et al., 2017; Feitosa et al., 2020). Thermal treatments applied during processing, while beneficial for microbial control, may accelerate the degradation of heat-sensitive compounds such as anthocyanins, thereby affecting color stability over time. These findings indicate that the development of liqueurs from fruit residues requires a careful balance between technological parameters and product quality attributes.

Despite the technological feasibility demonstrated across the analyzed studies, several limitations must be considered regarding the large-scale production of liqueurs from fruit residues. Most investigations are conducted under laboratory or small pilot-scale conditions, with limited evaluation of long-term stability, batch

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reproducibility, and industrial process integration. Additionally, the variability in residue composition, driven by differences in fruit origin, processing methods, and storage conditions, poses challenges for product standardization and quality control (Navarro-Martínez et al., 2019; Maurício et al., 2020). Sensory acceptance, although generally positive, is often assessed using small panels of untrained consumers, which may not accurately reflect market behavior. Therefore, although liqueur production from fruit residues represents a promising valorization pathway, its industrial application requires further validation, particularly in terms of process optimization, stability studies, and regulatory compliance.

4.5 Physicochemical, Sensory, and Functional Characterization of Alcoholic Beverages Produced from Fruit Residues

The physicochemical characterization of beverages from fruit residues shows parameters compatible with conventional beverages. Wines from fruit peels showed final TSS between 10.1 and 14.5°Brix and pH reduction from 4.5 to 3.65-3.78 (Okonkwo; Dilar, 2016; Balamaze; Wambete, 2017). Sensory evaluations indicated significant differences in aroma, acidity, and mouthfeel, while maintaining satisfactory consumer acceptance (Balamaze; Wambete, 2017; Méndez et al., 2022).

The functional composition has been highlighted due to bioactive compounds derived from residues. In orange peel tea wine, total flavonoids of 0.48 $mg \cdot mL^{-1}$ and total phenols of 2.32 $mg \cdot mL^{-1}$ were observed, with DPPH scavenging of 90.8% (Liu et al., 2025). Coutinho et al. (2024) reported that fermented beverages from jabuticaba peels had total phenolic content of 1597 mg $GAE.L^{-1}$ and antioxidant activity of 69%, higher than commercial red wine. Pereira et al. (2020) found that wheat beers with cashew peduncle and orange peel had polyphenol contents up to 726.6 ± 2.6 mg $GAE.L^{-1}$, with antioxidant activity proportionally correlated to fruit residues concentration. However, it is important to note that antioxidant activity was measured by in vitro assays (DPPH, ABTS, FRAP), which do not necessarily translate to in vivo health benefits.

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The analyzed studies consistently indicate that fruit residues represent a rich source of bioactive compounds, particularly phenolics and flavonoids, which contribute significantly to the antioxidant capacity of the developed beverages. In several cases, fermented beverages produced from fruit peels exhibited higher concentrations of bioactive compounds than conventional products, reinforcing their functional potential (Li et al., 2023; Coutinho et al., 2024). However, these outcomes are highly dependent on processing conditions, including fermentation time, temperature, and substrate composition, as well as the intrinsic variability of the raw materials (Navarro-Martínez et al., 2019; Maurício et al., 2020). Consequently, although bioactive enrichment is frequently reported, its reproducibility and stability under industrial conditions remain uncertain, requiring further standardization and validation of processing parameters.

A critical assessment of the literature reveals that, although sensory acceptance is frequently reported as favorable, important methodological limitations must be considered. Most studies rely on hedonic tests conducted with untrained consumers, typically involving sample sizes ranging from 30 to 100 participants (Salas-Millán et al., 2022; Dutra et al., 2023). While these approaches provide an initial indication of consumer perception, they lack the analytical precision required for detailed sensory characterization.

Studies employing descriptive sensory methods with trained panels, such as those applied to beers formulated with guaraná residues, enable a more comprehensive evaluation of attributes including intensity, persistence, and temporal dominance (Farias et al., 2020; Alves et al., 2021). Therefore, although overall acceptance scores are generally positive, the level of evidence varies substantially depending on the methodological rigor, and such findings should be interpreted with caution when considering large-scale market applicability.

4.6 Sustainability, Circular Economy, and Valorization of Agro-Industrial Residues

The significant generation of residues in fruit processing has been identified as a major environmental challenge, while simultaneously representing an important

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opportunity for value addition. The valorization of fruit residues in alcoholic beverage production is directly aligned with the principles of the circular economy, in which waste streams are reintroduced into productive systems as secondary raw materials (Silva et al., 2016; Coutinho et al., 2024). Several studies have demonstrated that fruit residues can be converted into products with commercial potential, contributing to income generation, cost reduction, and improved resource efficiency within agro-industrial systems (Balamaze; Wambete, 2017; Navarro-Martínez et al., 2019).

Beyond their direct application in beverage production, fruit residues can be integrated into broader circular bioeconomy strategies through cascading utilization systems. In this approach, biomass is sequentially converted into multiple value-added products, such as fermented beverages, bioactive extracts, and energy carriers, thereby maximizing resource efficiency and minimizing waste generation (Maurício et al., 2020; Coutinho et al., 2024). This cascading model is consistent with the biorefinery concept, in which different fractions of biomass are processed to generate a spectrum of products with varying economic value, ranging from functional ingredients to bioenergy (Silva et al., 2016; Navarro-Martínez et al., 2019). Such integration reinforces the transition from linear production models toward regenerative systems based on resource circularity.

The environmental benefits of fruit residue valorization are particularly relevant when considering the scale of agro-industrial waste generation. Inadequate disposal of these residues contributes to greenhouse gas emissions, especially methane, as well as soil and water contamination. Conversely, their transformation into value-added products reduces environmental burdens while promoting more efficient use of natural resources (Silva et al., 2016; Maurício et al., 2020). Studies indicate that the incorporation of fruit residues into production chains can reduce the environmental footprint of food systems, particularly when integrated into closed-loop production models (Feitosa et al., 2020; Coutinho et al., 2024). Thus, fruit residue valorization should be understood not only as a waste management strategy, but also as a key mechanism for environmental mitigation and sustainable production.

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From an economic perspective, the reuse of fruit residues contributes to value chain diversification and the creation of new market opportunities. The transformation of low-cost or discarded materials into commercially viable products, such as alcoholic beverages, extracts, and functional ingredients, enables the generation of additional revenue streams and enhances the economic resilience of agro-industrial systems (Balamaze; Wambete, 2017; Navarro-Martínez et al., 2019). This approach is particularly relevant for small-scale producers, for whom residue valorization may represent a low-cost strategy for product innovation and income generation. However, despite these advantages, comprehensive techno-economic analyses addressing large-scale implementation remain scarce in the literature, highlighting an important gap for future research.

Despite its conceptual and practical advantages, the implementation of circular economy strategies in fruit residue valorization is not without challenges. The efficiency of such systems depends on the availability of adequate infrastructure, technological integration, and regulatory alignment, which are often limited in real production contexts. Additionally, the intrinsic heterogeneity and perishability of fruit residues impose constraints related to collection, storage, and processing logistics, potentially limiting scalability and industrial feasibility (Silva et al., 2016; Coutinho et al., 2024). Therefore, although circular approaches represent a promising pathway toward sustainability, their effective implementation requires coordinated advances in technology, policy frameworks, and supply chain management.

4.7 Technological Challenges, Limitations, and Future Perspectives in the Use of Fruit Residues

The industrial application of fruit residue valorization in alcoholic beverage production faces a set of interconnected technological, safety, and regulatory challenges that remain insufficiently addressed in the current literature. One of the primary limitations lies in the predominance of laboratory-scale studies, typically conducted in small fermentation volumes ranging from 0.5 to 20 L, with only limited evidence available at pilot scale and no robust demonstrations at full industrial

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scale. This gap significantly constrains the translation of experimental findings into commercial production systems, as scale-up involves complex adjustments in process control, mass transfer, microbial dynamics, and product consistency (Balamaze; Wambete, 2017; Nascimento et al., 2018).

In addition to scale-related constraints, the inherent variability of fruit residues represents a critical barrier to process standardization. The chemical composition of these materials is strongly influenced by factors such as species, cultivar, maturity stage, cultivation conditions, and post-harvest handling. This variability directly affects fermentation performance, bioactive compound availability, and final product quality, thereby requiring the implementation of rigorous quality control strategies and potentially the development of standardized residue blends to ensure batch-to-batch consistency (Silva et al., 2016; Coutinho et al., 2024).

Food safety is another key concern that remains underexplored. Although some studies have reported adequate microbiological quality of the final beverages, systematic evaluations of potential chemical contaminants, such as pesticide residues, mycotoxins, and heavy metals, are largely absent. This is particularly relevant considering that many contaminants tend to accumulate in fruit peels, which are the primary residues used in these formulations. Consequently, the safe use of these materials requires comprehensive risk assessment protocols that go beyond conventional microbiological analysis (Feitosa et al., 2020; Pereira et al., 2020).

From a regulatory perspective, the incorporation of agro-industrial residues into food products presents additional challenges. In many jurisdictions, these materials are legally classified as waste rather than food ingredients, creating barriers to their commercialization. Compliance with existing legislation—such as standards for alcoholic beverages, labeling requirements, and safety regulations—demands clear reclassification frameworks, as well as the establishment of specific guidelines for the use of such residues in food systems (Brazil, Decree No. 6.871/2009; EU Regulation No. 110/2008).

Finally, sensory validation also requires further refinement. Most studies rely on small panels of untrained consumers, without robust validation of sensory

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protocols or reproducibility analysis. While reported acceptance scores are generally favorable, these findings may not reliably predict consumer behavior at a commercial scale. Therefore, future research should prioritize the use of trained sensory panels and standardized methodologies to strengthen the reliability of sensory data.

Taken together, these challenges indicate that, although fruit residue valorization represents a promising and sustainable strategy, its large-scale implementation requires significant advances in process standardization, safety assessment, regulatory adaptation, and sensory validation. Addressing these gaps is essential to enable the effective transition from experimental research to industrial application.

4.8 Limitations of the Present Review

This review has several limitations that should be explicitly acknowledged. First, the exclusion of gray literature (theses, dissertations, conference proceedings) may have introduced publication bias, as studies with negative or non-significant results are less likely to be published in peer-reviewed journals. Second, the search was limited to four databases (Google Scholar, SciELO, Scopus, CAPES Periodicals) and may have missed relevant studies indexed elsewhere, such as PubMed. Third, the heterogeneity of the included studies, in terms of residue types, beverage matrices, fermentation conditions, and outcome measures, precluded quantitative meta-analysis and required narrative synthesis. Fourth, the quality assessment, although performed using an adapted JBI checklist, used a tool not specifically validated for food technology reviews. Fifth, the predominance of laboratory-scale evidence limits the generalizability of conclusions to industrial settings. Sixth, potential language bias exists, as only articles in English, Portuguese, and Spanish were considered. These limitations do not invalidate the findings but rather qualify the strength of the inferences drawn.

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5. FINAL CONSIDERATIONS

This systematic review demonstrates that fruit agro-industrial residues represent a technically viable and potentially valuable resource for the production of alcoholic beverages, particularly due to their content of fermentable sugars and bioactive compounds such as phenolics, flavonoids, and anthocyanins. These components contribute to antioxidant activity, oxidative stability, and sensory complexity, supporting the development of differentiated products with added functional value.

However, a critical analysis of the available evidence reveals important limitations that restrict the robustness and generalizability of these findings. Most studies were conducted under laboratory-scale conditions and exhibit substantial methodological heterogeneity, including variations in fermentation parameters, extraction techniques, and analytical approaches. This lack of standardization compromises comparability between studies and limits the reproducibility of results. In addition, sensory evaluations are frequently based on small panels of untrained consumers, reducing the reliability of conclusions regarding market acceptance.

From a technological perspective, conventional processes such as fermentation and maceration remain predominant, while emerging approaches have shown potential to enhance process efficiency and product quality. Nevertheless, their application remains largely restricted to controlled experimental settings, with limited validation at pilot or industrial scale. Furthermore, aspects related to food safety, contaminant control, and regulatory compliance remain insufficiently addressed, representing critical barriers to commercial implementation.

From a sustainability standpoint, the valorization of fruit residues aligns with circular economy principles and offers clear environmental advantages by reducing waste generation and promoting resource efficiency. However, the effective integration of these materials into industrial systems depends on overcoming challenges related to raw material variability, process standardization, and supply chain logistics.

Overall, although the valorization of fruit residues in alcoholic beverage

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production is a promising and sustainable strategy, the current body of evidence remains limited in scope and maturity. Future research should prioritize methodological standardization, pilot-scale validation, comprehensive safety assessments, and techno-economic analyses to support the transition from experimental studies to industrial application.

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