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Supercritical CO_2 Extraction of Wine and Beer Yeast Residues for Sustainable Bioproduct Recovery

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***Abstract* – This paper presents a study on the use of supercritical carbon dioxide (SC-CO_2) extraction to isolate yeast metabolites from beer and wine matrices effectively. A major contributor to the flavour and aroma profiles of alcoholic beverages, yeast contains a rich reservoir of bioactive compounds that can be used in various industries, including food and pharmaceuticals. Conventional extraction methods often fail to obtain comprehensive and high-quality recoveries of these valuable metabolites. In response, this study explores the use of SC-CO_2, a green and tuneable solvent, to overcome the limitations of conventional extraction methods. The study investigates the influence of critical process parameters such as pressure, temperature, and extraction time on the yield and composition of extracted yeast metabolites. Advanced analytical methods (gas chromatography for the determination of fatty acids and high-performance liquid chromatography for the determination of the amino acid composition of the yeast residue left after extraction) are used in the analysis to characterize the chemical profile of the extracts. The results show that SC-CO_2 extraction offers a promising alternative to extract a diverse range of yeast-derived compounds, including flavour-enhancing esters, phenolic compounds, and bioactive peptides. The optimized extraction conditions show a significant improvement in extraction efficiency compared to traditional methods. Sensory analysis reveals that beverages produced with SC-CO_2-extracted yeast have distinctive and desirable flavour profiles. This research not only contributes to the development of extraction technologies in the beverage industry but also opens up new opportunities for the use of yeast-derived bioactive compounds in various applications. The environmentally friendly nature of SC-CO_2 extraction meets the growing demand for sustainable and clean technologies in food and beverage processing. Overall, the results of this study highlight the potential of SC-CO_2 extraction as a valuable tool for improving the extraction of bioactive yeast metabolites, thereby influencing the quality and sensory properties of beer and wine.**

***Keywords* – Added value products; amino acids; beer brewing by-products; by-products; by-products of wine production; extraction; fatty acids.**

1. INTRODUCTION

The valorisation of by-products from wine and beer production presents an opportunity to address both environmental concerns and resource efficiency. As the global demand for sustainability and waste reduction grows, the pursuit of innovative methods to recover high-value compounds from industrial by-products has become increasingly crucial. In this context, supercritical carbon dioxide extraction emerges as a clean and efficient technology

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capable of isolating bioactive compounds, such as fatty acids, from the residues of wine and beer yeast. The article discusses both the yeast obtained in the wine and beer production process, its processing steps and the obtained results.

Beer is one of the oldest and most widely appreciated alcoholic beverages, with the earliest evidence of its production dating back to around 6 000 years ago by the Sumerians. Over time, the brewing process has continuously evolved, leading to a wide variety of beers with unique characteristics often associated with their region of production. In recent years, beer production has embraced local grains and fruits, creating a link to specific geographical areas [1], [2].

The brewing process generates various by-products such as spent grain, spent yeast, and spent hops or hot hops [3]. While the use of by-products from large-scale breweries has been extensively studied to improve environmental and economic sustainability, there is limited understanding of how brewery by-products are utilized in breweries. Despite an extensive review of existing literature, there is a lack of information on waste disposal options and production strategies for beer. The brewing industry has experienced a significant increase in the number of breweries in many countries, gaining market share from major international breweries. However, the economies of scale may prevent a significant portion of the brewing industry, particularly breweries, from achieving similar economic benefits associated with the utilization of excess by-products observed in larger breweries [4]–[8].

Waste products from grape growing and winemaking include vine shoots, grape pomace (consisting of seeds, stems, and skins), wine lees, wastewater, and excess grape must. Vine shoots (VS) make up a significant portion of winery residues, with agronomic pruning practices contributing to up to 93 % of these residues [9]–[11]. Comprised of cellulose, hemicellulose, and lignin, VS can be used as a versatile platform for producing various biological products such as oligosaccharides, proteins, lactic acid, bioactive compounds, biosurfactants, xylitol, as well as biofuels like ethanol and biogas. Instead of resorting to incineration or landfill disposal, a more cost-effective and environmentally friendly approach involves utilizing VS as an energy source and for the production of value-added products [12], [13].

Researchers have explored the use of supercritical carbon dioxide and their liquid counterparts as effective solvents for producing value-added products in a sustainable and environmentally friendly way. Current research focuses on replacing toxic organic solvents with ecologically sound alternatives. Subcritical fluids, such as water and ethanol maintained above their boiling point but below their critical temperature, have demonstrated notable solvent capabilities in extracting various biological components from agricultural matrices [14]. The use of subcritical fluids addresses some of the drawbacks associated with supercritical carbon dioxide, such as limited affinity for polar solutes and high capitalization costs. Subcritical water has been effective in extracting essential oils, polyphenolic compounds, and eliminating food contaminants. It has also been used to extract health-promoting components from plants. Studies show that using hot pressurized water with ethanol as a co-solvent is successful in extracting polyphenolic compounds from plant sources. Additionally, a combination of hot pressurized water with supercritical carbon dioxide has been identified as effective in biomass transformation [15].

Wine yeast by-products, such as lees (residual yeast cells) and grape pomace (consisting of grape skins, seeds, and stems), contain fatty acids, which are a component of the cellular structure of yeast. These fatty acids contribute to the overall composition of wine yeast by-products and may have potential uses or applications in the fields of food, pharmaceuticals, or cosmetics. Understanding the fatty acid content in wine yeast by-products is important for exploring their nutritional value, functional properties, and possible industrial uses [16], [17].

Wine yeast by-products also contain a variety of amino acids, which are organic compounds that serve as the building blocks of proteins and play a crucial role in the biological processes of yeast cells. During winemaking, yeast utilizes and produces amino acids, which contribute to the overall composition of wine yeast by-products [18]. The specific amino acid profile in wine yeast by-products can vary depending on factors such as grape variety, fermentation conditions, and winemaking practices. Some commonly found amino acids in wine yeast by-products include glutamic acid, proline, arginine, and others. The presence of these amino acids in yeast by-products may have implications for their nutritional content and potential applications in various industries, including food, pharmaceuticals, and cosmetics. Researchers and industries often study and utilize the amino acid content in wine yeast by-products for their nutritional value and functional properties [19].

Beer yeast by-products, such as spent yeast or yeast slurry, contain a variety of fatty acids, which are vital components of yeast's cellular structure. During the beer fermentation process, yeast cells consume sugars, leading to the production of alcohol and carbon dioxide. As yeast cells grow and multiply, they accumulate fatty acids within their cellular membranes [20]. When beer is brewed, the yeast cells settle to form a sediment layer known as trub, which includes spent yeast and a mixture of various compounds, including fatty acids. The fatty acid profile in beer yeast by-products can be influenced by factors such as the used yeast strain, fermentation conditions, and the type of beer being brewed [21]. The fatty acids present in beer yeast by-products contribute to the overall flavour, aroma, and mouthfeel of the beer. Furthermore, the presence of fatty acids in spent yeast may have implications for potential uses or applications in other industries, such as food or animal feed. Understanding the composition of fatty acids in beer yeast by-products is crucial for exploring their nutritional value, potential functional properties, and possible applications in various fields [22].

The study carried out experiments to determine the oil content of beer and wine yeast and extract it using SC-CO_2 extraction. The aim of the study was to find the use of beer and wine yeast by-products from beverage factories to produce a value-added product. The resulting oil was also analysed.

2. Material and Methods

2.1. Material

Yeast residues after wine and beer production, are obtained from wine and beer production local facilities. The yeast residue was sublimated.

Two types of yeast were used in the processes (*Saccharomyces cerevisiae*). The first variant used yeast residues after the production of raspberry wine. At first, the ground berries ferment for a week, then they are squeezed and the resulting liquid is poured into another container, where the fermentation process continues for at least another two weeks. Yeast residues occur after active fermentation and settle to the bottom of the wine in about 1–2 months. These resulting by-products are discarded because no use has been found for them. In the second variant, yeast residues after the beer production process were used.

The yeast residue was sublimed. In a sublimator a freeze dryer removes water from a perishable material in order to preserve it, extending its shelf life and/or making it more convenient for transport. Freeze dryers work by freezing the material, then reducing the pressure and adding heat to allow the frozen water in the material to change directly to a vapor (sublimate).

2.2. Sample Preparation

Drying stands out as a crucial thermal procedure employed in food preservation. The primary objective of this process is to reduce the water content to a level that impedes enzymatic reactions and the proliferation of microorganisms. These factors could otherwise adversely impact the quality of the material undergoing drying [23].

Freeze drying, also known as sublimation, represents a dehydration technique conducted at low temperatures. This method involves freezing the product, subsequently releasing the pressure, and then eliminating the ice through freeze drying (or liofilisation, sublimation). In contrast to conventional dehydration methods, where water is evaporated using heat, lyophilized products exhibit exceptional quality. The original vitamins, proteins, other beneficial substances, and the product's form are retained, resembling the characteristics of the initial product [24]. Following drying, the samples were finely ground into powder using a food-grade mixer. Subsequently, all samples were carefully packaged and stored at temperatures ranging from −20 °C until further utilization.

2.3. Bligh and Dyer's Method

The Bligh and Dyer method was utilized to quantify the oil content. Six wine yeast and 12 beer yeast by-products samples were examined, with no water added to three samples and 5 mL of distilled water added to the remaining three. Water was additionally added because sometimes higher oil content in samples has been observed directly in samples with additional water added and oil amounts are compared for samples with and without additional water added. Sublimated yeast residue (1.5 g) was measured into 20 mL screw-cap tubes, along with 4 mL of methanol, 4 mL of chloroform, and glass beads. The mixture underwent 4 minutes of shaking in a homogenizer, followed by the addition of 2 mL of distilled water and another minute of shaking. Post-shaking, the samples were centrifuged at 8000 rpm for 15 minutes at 5 °C. Meanwhile, clean 10 mL beakers were weighed. After centrifugation, the samples were filtered using a glass filter in a 100 mL Bunsen flask with 3 µm filter paper. Following filtration, chloroform (2 mL) was added again to the biomass, shaking to separate the liquid fraction. The lower layer, obtained by pipetting 1 mL from the stratified filtrate, was carefully separated to avoid the upper layer entering the sample. With the flask tilted at a 45° angle, the pipette tip was dipped into the bottom layer to extract the oil from the sample [25]. The samples were then left to evaporate in a fume hood for a day and subsequently weighed to determine the oil quantity in the yeast.

2.4. SC-CO_2 Extraction

A green extraction method was chosen SC-CO_2 extraction. Two sizes of cylinders were used in the process; extraction was first performed using the smaller size cylinder (sample weight ~90 g) to fill the system with extract from yeast residues. The same pressures were used for wine and beer yeast residues. Extraction in the small cylinder was carried out at 250 bar for 3 hours. The large cylinder contained about 260 grams of yeast by-products. Extraction of wine yeast yielded no oil, so only amino acids were determined for this by-product. However, the extraction of brewer's yeast by-products only yields oil under specific conditions. In this process, solute or CO_2 was used at a constant flow (5.0 or 2.5 $cm^3\ min^{-1}$) at 280 bar pressure, at 30 °C for 3 h. After 3 h, the extracts were collected at 30 °C with several runs and 10–15 min between each collection. During extraction at 280 bar pressure, 2 % or 5 milligrams of brewer's yeast by-product oil was obtained. Fig. 1 shows the supercritical CO_2 extraction process, showing that after extraction, the oil sample was

collected as it flows through separators 1 and 2. In separator 1, the pressure was constant around 70 bar in all experiments, and in separator 2–60 bar.

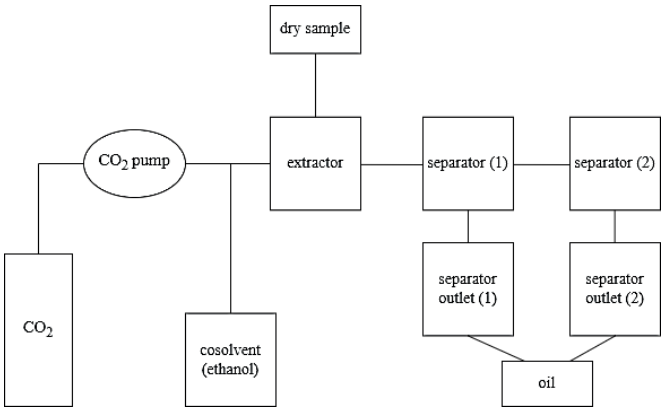

Fig. 1. Supercritical CO_2 extraction process.

2.5. Fatty Acid Profile of Extracts

Gas chromatography was used to analyse fatty acids profile of samples (as methyl esters). Analysis and sample preparation were done under conditions and using procedure described in [26], [27] with minor modifications. Briefly, 20 to 50 mg of sample was saponified by KOH solution in MeOH at 75 °C for 1 hour. Then, methylation procedure (transformation into methyl esters) was performed at 75 °C for 1 hour by addition of H_2SO_4. Extraction of fatty acids methyl esters was done using Hexane (HPLC grade) with addition of Methyl behenate (C22:0) (≥ 99.0 %) as an internal standard. Hexane layer was dried by anhydrous Na_2SO_4 prior to injection into GC. Identification and quantification of methyl esters was done using 37 components standard fatty acid methyl esters (FAMEs) mixture CRM47885.

Analysis was performed on Shimadzu GC-2030 gas chromatograph using capillary column Rt-2560 (100 m × 0.25 mm I.D., 0.20 μm). Chromatography conditions were as follows: oven – 180 °C isothermal for 32 min, ramped to 215 °C at 20 °C/min, hold 22.75 min; He constant flow rate – 2 mL/min; injector – 250 °C, detector (FID) – 250 °C, carrier gas He (flow rate 45.0 mL/min), make-up gas (He, flow rate – 24.0 mL/min; H2 – 32 mL/min, Air – 200 mL/min); injection – 1 μL (split ratio 20:1).

2.6. Amino Acids Analysis

Hydrolysis of samples: 20 to 50 mg of the dried cells (or yeast) were hydrolysed in 6M HCl/phenol solution at 110 ± 2 °C for 24 hours in so-called “sealed” tubes. Determination of Methionine as a Methionine sulfone and evaluation of Cysteine + Cystine amino acids content (as a Cysteic acid) was done after pre-oxidation of samples for 16 h at 0 °C by performic acid prior to hydrolysis using recommended protocols as described in [28] with minor modification.

Identification and quantification of amino acids was done using HPLC-grade reagents: amino acids standard mix (A9781-5 mL from Sigma Aldrich) and individual standards (L-Cysteic acid monohydrate, ≥ 99.0 %; DL-Methionine sulfone, ≥ 99.0 %). An automated in-needle pre-column derivatization of protein hydrolysates was done by Orthophthalic aldehyde in the presence of Mercaptopropionic acid (OPA/MPA) and 9-Fluorenylmethyl chloroformate (FMOC) [29].

HPLC analysis was performed on HPLC Shimadzu Nexera series using YMC-Triart column C18 (150 mm × 3.0 mm, 3 µm) with a guard column of the same type in gradient mode. The chromatography conditions were as follows: mobile phases: A – phosphate buffer pH 6.9; B – Acetonitrile : Methanol : H_2O = 45:40:15 (v/v/v); flow – 0.8 mL/min; column temperature – 40 °C, inj. volume – 0.3 µL. Gradient elution program was similar to described in [30] and fluorescence UV-Vis detection was done on two channels: Ex. – 350 nm, Em. – 450 nm; Ex. – 266 nm, Em. – 350 nm.

Tryptophan determination: Procedure for Tryptophan determination was similar to described by [31], [32] with some modifications. Briefly, 20 to 50 mg of the dried cells (or yeast) were hydrolysed in 4.2 N NaOH at 110 ± 2 °C for 20 hours under nitrogen atmosphere. Then hydrolysates were neutralized by 6N HCl on ice. Identification and quantification of Tryptophan was done using standard sample of HPLC-grade Tryptophan (> 98.5 %) and standard amino acids mix A9781. HPLC analysis was performed on HPLC Shimadzu Nexera series using Kinetex C18 column (150 mm × 3.0 mm, 3 µm) with a guard column of the same type in isocratic mode. The chromatography conditions were as follows: mobile phase – acetate buffer pH 6.3: Acetonitrile = 90:10 (v/v); flow – 0.5 mL/min; column temperature – 30 °C; inj. volume – 10 mkL. Spectrophotometric detection of Tryptophan was done at excitation wavelength 280 nm and emission wavelength 340 nm.

Uncertainty of amino acid content determination is approx. ± 10 % relative.

3. RESULTS AND CONCLUSIONS

The results show that the oil content of the wine yeast is only 2 % and the additional water does not show better results than 1 %. However, the situation is better in brewer's yeast, as the oil content of the samples without additional added water was on average 8 %. The results are shown in Table 1.

TABLE 1. OIL AMOUNT IN YEAST

	Nr.	Sample weight, g	Oil amount, g	Oil amount, %	Oil in 1 g sample, g
Yeast residues from wine	1	1.52	0.03	2.04	0.020
	2	1.53	0.03	1.99	0.020
	3	1.53	0.03	2.01	0.020
	4	1.52	0.02	1.04	0.010
+5 mL H_2O	5	1.5	0.02	1.13	0.011
	6	1.45	0.01	0.64	0.006
Yeast after beer	1	1.5	0.12	8.00	0.080
	2	1.49	0.14	9.40	0.094
	3	1.49	0.17	11.41	0.114
+5 mL H_2O	4	1.55	0.08	5.16	0.052
	5	1.57	0.11	7.01	0.070
	6	1.49	0.05	3.36	0.034
Yeast residues from beer (grapefruit)	1	1.46	0.14	9.59	0.096
	2	1.55	0.13	8.39	0.084
	3	1.47	0.15	10.20	0.102
+5 mL H_2O	4	1.56	0.12	7.69	0.077
	5	1.46	0.12	8.22	0.082
	6	1.57	0.1	6.37	0.064

Two samples of fatty acids obtained after supercritical extraction of brewer's yeast were analysed. The results show that the total fatty acid content of the samples was 11 %. The results show that fatty acids are not abundant, but this can be explained by the maximum pressure available in the SC-CO_2 equipment, but in future studies, improving the equipment (pressure up to 400–500 bar) would allow more fatty acids to be obtained [33]. It should also be noted that in the scientific publications brewer's yeast was extracted at lower pressures (200 bars) [34]. The most saturated fatty acids (75.89 %) were found in the sample, which will be discussed further in the conclusions, as well as products with added value that can be produced using the oil obtained during the extraction process of brewer's yeast. Result shown in Table 2.

TABLE 2. FATTY ACID IN BEER YEAST

Fatty acid (FA) composition			
Fatty acid		**Average** (wt. % of total FA)	**RSD**
Caproic acid	C6:0	0.28	0.01
Caprylic acid	C8:0	0.98	0.48
Capric acid	C10:0	2.55	1.51
Lauric acid	C12:0	1.03	0.04
Myristic acid	C14:0	5.22	0.32
Pentadecanoic acid	C15:0	1.13	0.06
Palmitic acid	C16:0	58.22	3.63
Margaric acid	C17:0	0.52	0.03
Stearic acid	C18:0	4.25	0.27
	Total SFA	**75.89**	**2.41**
Oleic acid (ω-9)	9c-C18:1	3.04	0.14
Vaccenic acid (ω-7)	11c-C18:1	0.45	0.04
	Total MUFA	**3.49**	**0.18**
Linoleic acid (ω-6)	C18:2n-6	9.99	0.48
Docosapentaenoic acid (Osbond acid) (ω-6)	C22:5n-6	0.71	0.20
	Total n-6 LC-PUFA	**11.20**	**0.65**
α-Linolenic acid (ω-3)	C18:3n-3	5.89	0.92
Docosahexaenoic acid, DHA (Cervonic acid) (ω-3)	C22:6n-3	3.15	0.94
	Total n-3 LC-PUFA	9.43	1.94
	Total cis-PUFA	**20.62**	**2.59**
$W_{FA,}$ % (wt. % of total sample mass)		**11.1**	**2.3**

Analysing the protein content of the samples, it was concluded that the sample contains 22 % protein. The obtained results show that wine yeast contains mainly two types of amino acids, aspartic acid (10.68 %) and glutamic acid (13.37 %). These essential amino acids are very important for human health, for example, aspartic acid participates in the synthesis of other amino acids and is involved in energy production and the functioning of the nervous system, while glutamic acid is important for the functioning of the human body. the brain because it acts as a neurotransmitter. It is also involved in energy metabolism and the synthesis of other amino acids. The results are shown in Table 3.

TABLE 3. AMINO ACIDS IN WINE YEAST

Amino acids profile of Raspberry wine yeast biomass			**Amino acids profile of Beer yeast biomass**	
Amino acid	g/ (100 g sample)	m %, in pure protein	g/ (100 g sample)	m %, in pure protein
Aspartic acid	2.34	10.68	2.06	12.42
Glutamic acid	2.93	13.37	2.29	12.72
Serine	0.88	4.02	0.66	3.86
Histidine	0.50	2.27	0.43	2.41
Glycine	1.07	4.87	0.94	5.21
Threonine	1.29	5.90	0.80	4.43
Arginine	1.05	4.77	0.93	5.16
Alanine	1.29	5.87	0.97	5.40
Tyrosine	0.97	4.43	0.68	3.79
Cysteine	0.13	0.59	0.18	1.06
Valine	1.40	6.40	0.93	5.17
Methionine	0.61	2.63	0.47	2.73
Tryptophan	0.38	1.62	0.36	2.04
Phenylalanine	0.91	4.15	0.78	4.32
Isoleucine	1.26	5.76	0.83	4.61
Leucine	1.75	7.99	1.27	7.06
Lysine	1.64	7.49	1.00	5.52
Proline	1.58	7.19	2.39	13.27
Protein content, W (mass % of dried sample)	22.0	± 0.30	18.0	± 1.0

It was concluded that the sample contains 18 % protein. The obtained results show that wine yeast contains the mostly three types of amino acids: aspartic acid (12.42 %), glutamic acid (12.72 %) and proline (13.27 %). These essential amino acids are very important for human health, for example, aspartic acid plays a role in the synthesis of other amino acids and is involved in energy production and the functioning of the nervous system, and glutamic acid is important for the functioning of the brain because it acts as a neurotransmitter. It is also involved in energy metabolism and the synthesis of other amino acids. As well as proline, which is involved in the synthesis of collagen, a structural protein that provides support for various body tissues.

This investigation into beer yeast by-products, characterized by a substantial 75.89 % saturated fatty acid content, unveils intriguing prospects for value-added product development. The rich fatty acid composition presents a novel avenue for targeted nutritional solutions. Foremost among these is the potential extraction and concentration of omega-3 fatty acids, offering a basis for formulating supplements that can positively impact cardiovascular health and overall well-being.

The study utilized gas chromatography to analyse the extracted fatty acids from the beer yeast. The reported data shows a high content of saturated fatty acids, with a particularly large proportion of palmitic acid (C16:0) at 58.22 % weight by weight of total fatty acid (wt. % of total FA). The results also indicate the presence of monounsaturated fatty acids like oleic acid (C18:1) making up 3.49 % of the total FA, as well as polyunsaturated fatty acids with linoleic

acid (C18:2) at 9.99 % and alpha-linolenic acid (C18:3) at 5.89 % of total FA. Considering the obtained results, it is valuable to look at products with added value that can be produced from the obtained extracts. For example: 1. Food supplements. The high content of omega-3 fatty acids (such as alpha-linolenic acid) can be used to create cardiovascular health supplements and products aimed at improving general well-being. 2. Functional cooking oils. The extracted fatty acids can be used to develop healthier cooking oils that offer a unique nutritional profile compared to conventional oils. 3. Keto friendly products. Due to their high level of saturated fatty acids, they can be integrated into ketogenic diet products, including snacks, nutrition bars, and meal replacement shakes, which are popular among consumers looking for high-energy, low-carb options. 4. Weight control supplements. The satiating effect of some fatty acids can be used in dietary supplements to help control appetite and promote healthier eating habits. 5. Animal feed additives. The nutritional value of livestock and poultry diets can be improved by integrating these fatty acids into their feed, thereby improving animal health. The study concludes that these fatty acid profiles of the beer yeast by-products can be potentially valuable for developing targeted nutritional products, such as omega-3 fatty acid supplements, functional cooking oils, weight management supplements, and could also find applications in animal feed.

Regarding amino acids, the study mentions the primary amino acid composition obtained from wine and brewer's yeast extracts, such as glutamic acid, aspartic acid and alanine. These amino acids are important because of their role in various physiological functions:

- Glutamic acid: It functions as a neurotransmitter that is vital for brain activity and is involved in energy metabolism and the synthesis of other amino acids.
- Aspartic acid: It has a role in synthesizing other amino acids.

Considering the obtained results, it is valuable to look at products with added value that can be produced from the obtained extracts. For example: 1. Amino Acid Supplements. Targeted health supplements can be formulated using specific amino acids like glutamic acid and aspartic acid to support muscle health, energy levels, and cognitive function. 2. Sports Nutrition. Products like energy bars or drinks can exploit the roles of these amino acids in energy metabolism and post-exertion muscle recovery, which is especially beneficial for athletes. 3. Post-Workout Recovery Drinks. Supplements that focus on a balance of aspartic acid and glutamic acid could help with muscle recovery and reduce fatigue after exercise. 4. Functional Beverages. Enhanced waters and fruit drinks can incorporate these amino acids to promote overall health, hydration, and possibly cater to specific demographics like seniors and children. 5. High-Protein Snacks and Protein Powders. For convenience-focused consumers, incorporating these amino acids into protein-rich snacks or instant mixes can cater to those needing quick and effective protein supplementation. 6. Beauty and Wellness Products. Aspartic acid and glutamic acid can also play a role in skincare, potentially being used in collagen supplements and beauty drinks to promote skin health and collagen production. 7. Plant-Based Protein Sources. For vegan consumers, brewer's yeast by-products rich in these amino acids can be utilized to develop plant-based protein powders. Through our investigation into the SC-CO_2 extraction of bioactive compounds from wine and beer yeast residues, we have demonstrated a method that can potentially transform waste into sustainable bioproducts. As we look to the future, we have identified several areas where further research and development could expand the application and efficacy of this approach.

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