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Exploring the potential of anthocyanin-infused fermented beverages for sustainable health solutions: A pathway to functional food development

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ABSTRACT

Anthocyanins, natural red pigments in foods, have gained significant attention due to their potent antioxidant, anti-inflammatory, and anti-microbial properties. Among food products, beverages especially fermented ones emerge as candidates for anthocyanin fortification due to their global popularity and potential to deliver substantial health benefits in diets. This review particularly highlights the health promoting potential of anthocyanin-rich fermented dairy and non-dairy fermented beverages such as kefir, kombucha, and kvass focusing on their health benefits such as cognitive function, type 2 diabetes (T2DM) and cancer. And also, emphasizes the functional roles of beverages in gut microbiota modulation, metabolic and neurotransmitter regulation, oxidative stress reduction and signaling pathways (e.g., NF-κB, PI3K/AKT). Fermentation technologies and innovative stabilization methods are presented as critical for preserving anthocyanin integrity, enhancing bioavailability, and improving both nutritional and sensory properties. Innovative technologies such as controlled fermentation, encapsulation, and use of fruit byproducts improve anthocyanin retention and functionality. By addressing current limitations in anthocyanin stability and exploring innovative solutions for fortification, this research contributes to the development of sustainable, health-oriented fermented beverages. The insights provided pave the way for expanding the functional beverage market while offering a roadmap for future studies to optimize the therapeutic and nutritional potential of anthocyanin-rich products.

1. Introduction

The growing awareness during the pandemic has significantly increased interest in functional foods. This consciousness has positively impacted the functional beverages market, with an expected increase from $21.4 billion in 2022 to $324.4 billion by 2027 with an annual growth rate of 8.4% for the 2022–2027 period (Palencia-Argel et al., 2024a). The inclusion of beneficial microorganisms specifically probiotics, along with prebiotics in the form of synbiotic supplements, not only meets daily nutritional requirements but also provides valuable nutraceutical benefits that contribute significantly to the enhancement and maintenance of human health. They play a central role in both supplementing and regulating the digestive system by supporting gut health (Dahiya and Nigam, 2023). Nowadays, consumers have turned to purchased foods, especially those containing probiotic bacteria or prebiotics due to their positive effects on health (Özcan et al., 2021; Ballini et al., 2023). Today, the most common products containing probiotics are generally fermented beverages including dairy and non-dairy beverages.

Fermentation is one of the methods used from ancient times to preserve seasonal and short-shelf-life foods, increasing nutritional value and digestibility (Singh et al., 2023; Shiby and Mishra, 2013). In this context, incorporating fermented products known for their diverse benefits into the daily diet can display various biological properties such

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as antioxidant, anti-inflammatory, anticancer and antihypertensive (Hidalgo-Fuentes et al., 2024). Therefore, the fermentation process has become significant due to its health benefits along with its capacity to preserve food. Today, more than 5000 fermented foods are consumed worldwide (Ray et al., 2024). It is important to note that fermented beverages can be broadly categorized into two major groups: dairy-based and non-dairy-based fermented beverages. Dairy-based beverages, such as kefir and koumiss, are produced from milk, while non-dairy-based beverages utilize plant-derived raw materials. This distinction is critical to avoid confusion, particularly when discussing the application of functional compounds such as anthocyanins.

Fermented beverages have traditionally been derived from milk, with kefir being one of the most well-known. Another notable fermented dairy product is Koumiss, a slightly alcoholic and tangy beverage traditionally produced from mare's milk. This product undergoes fermentation through the combined action of lactic acid bacteria and yeasts, which contribute to its distinctive flavor and properties. Koumiss is valued for its probiotic content and has been consumed for centuries, particularly in Central Asia, for its perceived health benefits (Kondybayev et al., 2021).

On the other hand, fermented beverages have been traditionally produced in various regions across the globe, utilizing diverse raw materials that do not include milk as a base ingredient. Notable examples of such beverages include cider, which is made from fermented apples; mead, a fermented drink derived from honey; sake, a traditional Japanese beverage created through the fermentation of rice, using koji and moto as essential microbial starters; and kombucha, a fermented tea beverage commonly prepared with black tea and symbiotic cultures of bacteria and yeast. Each of these beverages reflects unique regional practices and cultures, with distinct fermentation processes that contribute to their characteristic flavors, aromas, and potential health benefits (Cavia et al., 2023; Mendes-Ferreira et al., 2010; Akaike et al., 2020; Coelho et al., 2020). In addition to these traditional examples, a wide array of industrially produced fermented beverages derived from fruits, grains, and plants further enriches the diversity of fermented products available in the modern market. These beverages, often developed through advanced fermentation technologies, not only expand the spectrum of flavors and functional properties but also cater to growing consumer demands for health-promoting and innovative drink options. The incorporation of various raw materials and specialized fermentation processes has enabled the production of unique beverages, highlighting the versatility and adaptability of fermentation as a method of food and beverage innovation. When considering the application of bioactive compounds such as anthocyanins, it is therefore essential to separately evaluate their use in dairy-based fermented beverages and plant-based fermented beverages, due to differences in matrix composition, fermentation microbiota, and stability of these compounds. In dairy matrices, such as yogurt and kefir, anthocyanins interact predominantly with milk proteins, including caseins and whey proteins. These interactions can lead to the formation of protein–polyphenol complexes, which may either stabilize or destabilize anthocyanins depending on various factors such as pH, temperature, and the specific protein and anthocyanin structures involved. For instance, studies have indicated that the binding of anthocyanins to milk proteins can protect these compounds from degradation during storage, thereby preserving their antioxidant properties. However, the extent of this protective effect can vary based on the type of anthocyanin and the fermentation conditions employed. Conversely, plant-based fermented beverages, including those derived from soy, legumes, and cereals, present a different compositional matrix. These matrices often contain higher levels of phenolic compounds, such as isoflavones, which can engage in co-pigmentation interactions with anthocyanins. Such interactions have been shown to enhance the color stability and antioxidant capacity of anthocyanins during storage. For example, research has demonstrated that soy-based yogurt alternatives exhibit higher half-life values for anthocyanins compared to traditional dairy yogurts, suggesting improved stability in plant-based matrices. Additionally, the absence of certain dairy proteins in plant-based beverages may reduce the potential for anthocyanin-protein complexation that could lead to pigment precipitation or degradation.

Natural preservatives generated through fermentation offer multiple advantages, including enhancing the nutritional profile of foods by promoting the production of essential vitamins and antioxidants. Additionally, they play a critical role in extending shelf life and improving food safety, thereby addressing key concerns in food preservation (Anumudu et al., 2024). While the original ingredients in fermented products inherently provide substantial health benefits, these effects can be amplified by incorporating other bioactive compounds, resulting in products that are even more advantageous for human health. A wide variety of plant-based sources, such as fruits, vegetables, and herbs, serve as excellent substrates for fermentation processes, enabling the creation of nutrient-dense and functional products. This study focuses on fermented beverages derived from anthocyanin-rich fruits, which are recognized for their potential health-promoting properties, discussing their preparation, composition, and implications for human well-being.

Anthocyanins (ACNs) are natural pigments classified within the flavonoid subclass of polyphenols, representing the most prominent water-soluble polyphenols found in nature. These secondary metabolites are responsible for producing a wide range of vibrant colors, from red to purple and blue, depending on their structural composition and environmental pH. Their presence is widespread across various fruits, vegetables, and flowers, making them key contributors to the aesthetic and nutritional qualities of plant-based foods (Menconi et al., 2024; Xu et al., 2024). To date, more than 700 distinct anthocyanins have been identified, showcasing their remarkable diversity. Among the most prevalent anthocyanidin structures (aglyca of anthocyanins) are cyanidin (Cy), delphinidin (Dp), malvidin (Mv), peonidin (Pn), petunidin (Pt), and pelargonidin (Pg). These compounds play critical roles not only in plant physiology, such as attracting pollinators and providing protection against environmental stressors but also in human health, due to their potent antioxidant and anti-inflammatory properties (Mattioli et al., 2020; Teixeira et al., 2023; Lakshmikanthan et al., 2024). Figure 1 provides a detailed depiction of the basic structure of selected anthocyanins (ACNs) along with their potential fruit sources, offering a clear visualization of the diversity and natural distribution of these bioactive compounds. The primary sources of anthocyanins include a wide variety of red and dark-colored fruits, such as blueberries, black currants, blackberries, cranberries, raspberries, strawberries, cherries, pomegranates, and red or purple grapes. Additionally, several dark-colored vegetables, including red cabbage, eggplant, purple potatoes, and red onions, are also rich in anthocyanins (Lakshmikanthan et al., 2024; Gachovska et al., 2010; Ito and Lacerda, 2019; Šimerdová et al., 2021; Lianza et al., 2022; Qi et al., 2023).

Anthocyanins (ACNs) have garnered significant attention as key ingredients in functional food products, primarily due to their potent antioxidant, antimicrobial properties, and promising prebiotic potential (Palencia-Argel et al., 2024b). Their antioxidant capabilities enable them to effectively neutralize reactive oxygen species (ROS), contributing to the reduction of oxidative stress and promoting overall health (Menconi et al., 2024; Xu et al., 2024). In recent years, the role of fermented beverages enriched with ACNs has become a focal point in the development of functional food products. These beverages not only support public health but also contribute to a sustainable food economy by offering nutrient-dense options to consumers in an increasingly fast-paced and health-conscious society.

The production of anthocyanin-enriched beverages, particularly fermented ones, begins with the effective extraction of bioactive anthocyanins from natural sources to ensure their maximum yield and bioactivity preservation throughout the beverage production process. A notable portion of natural pigments in anthocyanin-rich sources remains intact in beverages produced through yeast fermentation. However, as

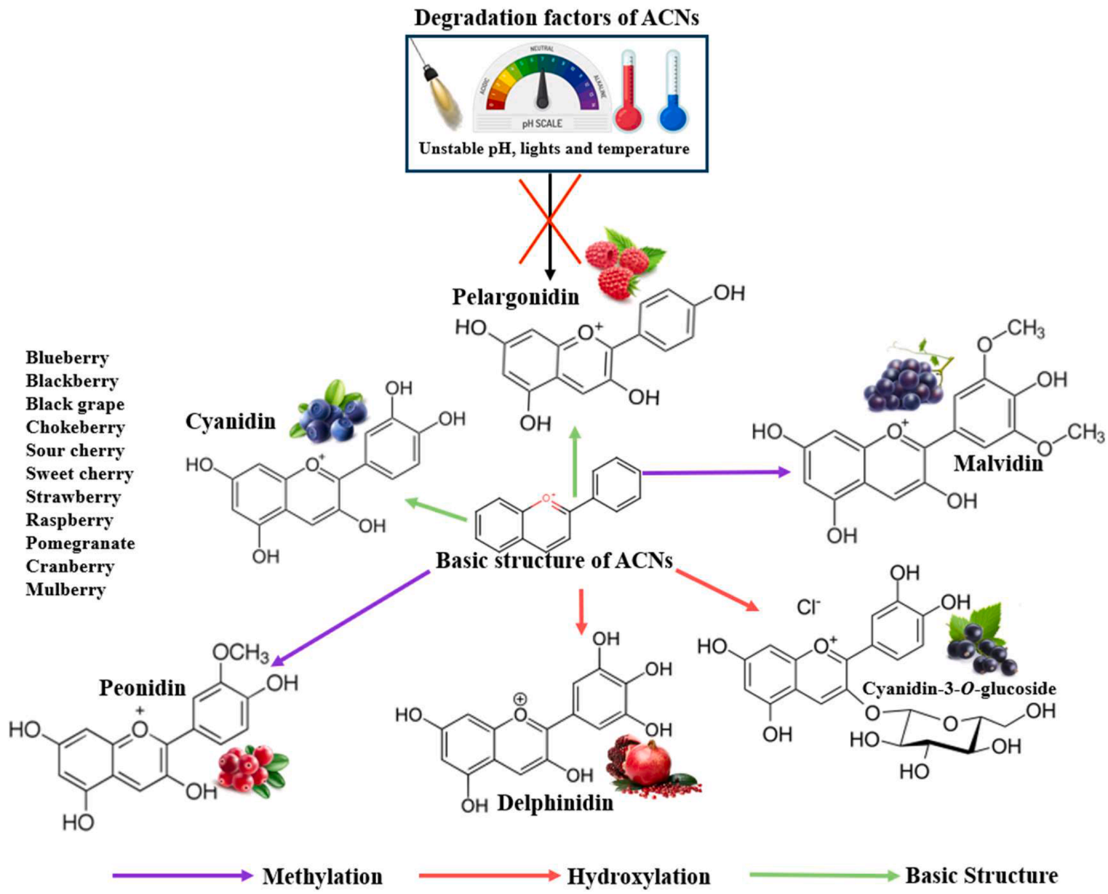

Fig. 1. Basic chemical structure of anthocyanins (Created from Reaxy.com and Freepik).

illustrated in Figure 2, anthocyanins undergo degradation during fermentation, resulting from interactions with glycolytic products such as pyruvate and acetaldehyde or with other compounds present in the complex fermentation medium. For instance, vinylphenols, derived from cinnamic acids through yeast decarboxylase activity, can form more stable pigments than the original anthocyanins. Figure 2 represents the initial fermentation of anthocyanins by probiotic microorganisms including Lactococcus lactis spp. lactis, Lactobacillus brevis, Lactobacillus plantarum, and Saccharomyces cerevisiae. This step aims to produce an anthocyanin-rich fermented beverage. This fermentation process not only preserves anthocyanins but also enhances their stability and bioavailability by microbial metabolism, B details the chemical transformation of anthocyanins during fermentation. During fermentation, microbial metabolism via intermediates like pyruvic acid leads to the formation of carboxy-pyranoanthocyanin derivatives from anthocyanin-3-*O*-glucoside the primary anthocyanin structure, and C highlights the health-related impacts of the fermented anthocyanin derivatives. Carboxy-anthocyanidins exhibit strong antioxidant and anti-inflammatory activities. Additionally, certain microorganisms involved in the fermentation process exhibit probiotic properties. These microorganisms contribute to gut health by supporting the digestive system, enhancing immune function, and maintaining intestinal flora balance (Louw et al., 2023). Through this process, anthocyanins play a crucial role in mitigating reactive oxygen species (ROS) and DNA damage within the metabolic system. They also exhibit resistance to oxidative degradation, helping to reduce inflammation. As a result, yeast-fermented beverages are valuable dietary sources of antioxidants, contributing not only to the overall chemical composition of the beverage but also to its organoleptic properties, thereby enhancing the sensory qualities of the final product (Ruta and Farcasanu, 2019).

This review delves into the dynamic changes anthocyanins undergo during yeast-mediated fermentation, the strategies employed to enrich fermented beverages with anthocyanins and their derivatives, and the intricate interactions between yeast and anthocyanins. These relationships are pivotal in producing high-quality beverages with optimal levels of anthocyanins and their derived compounds. The study underscores the significant potential of anthocyanin-rich fermented products, highlighting their dual importance. Firstly, as functional beverages, they offer promising health benefits, and secondly, they serve as a versatile medium for incorporating beneficial microorganisms into diverse formulations. By addressing these aspects, the review aims to contribute to the development of innovative, health-promoting fermented beverages while advancing the understanding of the metabolic and functional roles of anthocyanins in fermentation processes.

2. Extraction of bioactive anthocyanins

Anthocyanins are glycosylated derivatives of anthocyanidins, characterized by a core structure containing the flavylium cation. Typically located in plant vacuoles, these compounds are associated with sugars and organic acids, rendering them highly polar and water-soluble. The efficiency and quality of anthocyanin extraction are influenced by various factors, including the plant source, the solvent used, the complexity of the matrix (such as the presence of proteins and carbohydrates), anthocyanin concentration and variation, plant maturity, and cultivation conditions (Sendri and Bhandari, 2024).

Extraction methodologies for anthocyanins are broadly categorized into conventional and non-conventional techniques. Conventional extraction typically employs solvents such as ethanol, methanol, or aqueous acidic solutions. Although these methods are simple and cost-effective, they often involve significant disadvantages, such as the use of toxic solvents, risk of anthocyanin degradation due to prolonged

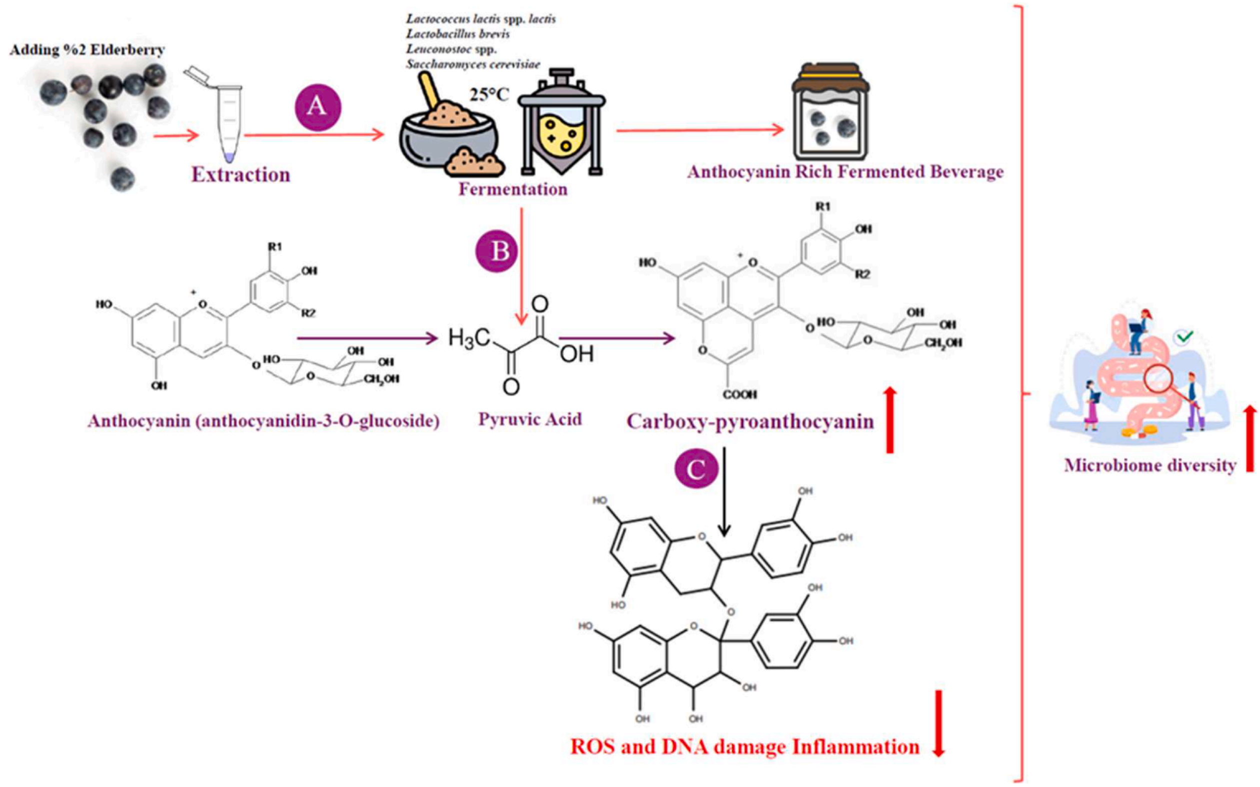

Fig. 2. Production of anthocyanin-rich beverages processes and their health effects (Created from Reaxy.com and Freepik) A. Extraction and fermentation process, B. Metabolic conversion of anthocyanins, C. Biological effects of carboxy-pyranoanthocyanins.

exposure to heat, and low selectivity toward target compounds. Additionally, long processing times may result in the loss of anthocyanin bioactivity, limiting the application of the final extract in food and pharmaceutical products. (Teixeira et al., 2023; Oteiza et al., 2023; Tena and Asuero, 2022; Ijod et al., 2022). To overcome these challenges, non-conventional extraction techniques have been developed, offering numerous advantages. These include microwave-assisted extraction, pulsed electric field extraction, enzyme-assisted aqueous extraction, and pressure fluid extraction. Microwave-assisted extraction, for instance, significantly reduces extraction time and solvent consumption but may lead to local overheating and possible degradation of heat-sensitive anthocyanins. Pulsed electric field extraction enhances cell permeability and facilitates compound release under mild conditions, yet requires high initial equipment investment. Enzyme-assisted extraction improves yield and selectivity by degrading cell wall components but is highly dependent on enzyme specificity and stability. Pressurized liquid extraction achieves high efficiency with low solvent volumes; however, careful optimization of temperature and pressure conditions is necessary to prevent anthocyanin degradation. Compared to traditional methods, these modern approaches enhance extraction efficiency, minimize solvent use, reduce energy consumption, and significantly shorten processing times. Furthermore, advanced technologies aim not only to increase extraction yields but also to lower environmental impact and improve the stability of anthocyanins throughout the process.

Stability regulation strategies, such as spray drying, nanoencapsulation, the incorporation of antioxidant additives like ascorbic acid, and optimized storage conditions, are essential to preserving anthocyanin bioactivity and functionality during and after extraction (Teixeira et al., 2023; Bitwell et al., 2023). Each extraction method brings unique benefits and challenges, influencing critical parameters such as yield, purity, stability, and the chemical composition of the extracted anthocyanins (Farooq et al., 2020). Therefore, the selection of the appropriate extraction method must be based on a thorough evaluation of the plant matrix characteristics, targeted anthocyanin profiles, final application purpose, and economic feasibility. The adoption of efficient and sustainable extraction techniques is critical for maximizing the bioavailability and functionality of anthocyanins, ensuring their applicability in food, pharmaceutical, and nutraceutical industries while addressing environmental and economic concerns.

A variety of advanced techniques have been developed and optimized for the extraction and isolation of anthocyanins from plant sources, offering enhanced efficiency, specificity, and yield. For instance, a study demonstrated the use of natural deep eutectic solvents combined with ultrasonic-assisted extraction to isolate cyanidin-3-*O*-galactoside (Cy3-gal) from *Rhododendron arboretum* (Singh et al., 2024). Similarly, peonidin-3-*O*-glucoside-5-*O*-glucoside content and overall anthocyanin composition were effectively optimized using High-Performance Liquid Chromatography (HPLC) coupled with Mass Spectrometry (MS), providing precise qualitative and quantitative analysis (Rosas et al., 2024). In another investigation, reversed-phase medium-pressure liquid chromatography (RP-MPLC) was employed for the rapid and efficient isolation of cyanidin-3-*O*-glucoside (C3G) and peonidin-3-*O*-glucoside (P3G) from black rice, showcasing the technique's effectiveness for anthocyanin purification (Jeon et al., 2015). Ultrasound-assisted extraction (UAE) has gained popularity as a method to significantly enhance anthocyanin yield while reducing extraction time. This approach is particularly effective for extracting anthocyanins from berries and other anthocyanin-rich fruits. However, this method may sometimes cause partial degradation of anthocyanins if ultrasound intensity and exposure duration are not properly optimized (Kumar et al., 2019).

Further advancements include the identification of anthocyanidins, such as delphinidin, cyanidin, and malvidin, from purple sweet potato using Ultra-High-Performance Liquid Chromatography coupled with Photodiode Array detection (UHPLC-PDA) (Sumartini, 2023). Enrichment of anthocyanins from sources like pomegranate and lingonberry has been achieved using XAD-7 column chromatography, followed by fractionation into anthocyanin-rich and co-pigment fractions using membrane chromatography (Kostka et al., 2020; Kostka et al., 2022). Countercurrent chromatography (CCC) is another innovative technique employed to isolate anthocyanins with high purity and efficiency (Esatbeyoglu et al., 2017). While CCC provides excellent recovery rates without the need for solid supports, the process can be time-consuming and requires careful solvent system selection for optimal performance. As depicted in Figure 3, the apparatus and setups associated with these extraction and separation methods are illustrated. Each technique offers unique advantages, enabling the efficient and selective extraction of anthocyanins from various plant sources. These advancements underscore the importance of tailoring extraction methods to specific plant matrices and desired anthocyanin profiles, paving the way for broader applications in food, pharmaceutical, and nutraceutical industries.

3. Fermented beverages using anthocyanin-rich foods

Emerging technologies, including controlled fermentation utilizing specific strains of microorganisms and advanced stabilization techniques, play a pivotal role in optimizing the retention and stability of anthocyanins in fermented beverages (Du and Myracle. 2018). Anthocyanins, which have garnered significant attention in recent years due to their myriad health benefits, are highly susceptible to degradation and instability. Several factors influence their stability, including pH, temperature, light exposure, relative humidity, sugars, vitamin C, oxygen levels, sulfur dioxide and sulfites, enzymes, pigments, and metal ions etc. (Singh et al., 2018). Research has demonstrated that anthocyanin degradation during high-temperature storage is often accompanied by an increase in polymeric color values, suggesting intense polymerization of anthocyanins (Aşkın and Atik, 2016). To mitigate such degradation, innovative methods such as ultrasound processing and protective encapsulation techniques have been employed to enhance the stability of anthocyanins. However, further investigation is necessary to explore the potential of newer techniques and refine existing ones to improve the long-term retention of these bioactive compounds in fermented products (Du and Myracle, 2018). Notably, studies have shown that lactic acid, glucose, and specific microorganisms significantly impact the stability and color of anthocyanins, particularly in kefir, highlighting the importance of fermentation conditions in preserving anthocyanin integrity (Kabakcı et al., 2020).

Functional fermented beverages are recognized for their antioxidant, antimicrobial, and prebiotic properties, and their health-promoting potential can be further augmented by incorporating anthocyanin-rich foods into their formulations. The preparation of fermented anthocyanin-enriched beverages, as illustrated in Figure 4, showcases a promising approach to delivering both health benefits and organoleptic appeal (Palencia-Argel et al., 2024b; Barazi and Arslan, 2024). These advancements underscore the potential of fermented beverages as vehicles for enhancing the bioavailability of anthocyanins, thereby contributing to the growing interest in functional foods and beverages with enhanced nutritional value.

Kefir, a traditional dairy product derived from kefir grains, is a unique fermented beverage comprising a specific mixture of yeast and bacteria. It is produced by inoculating milk with "kefir grains," which impart a distinctive sour taste and creamy texture to the beverage (Dimidi et al., 2019). Recently, the demand for healthier beverage alternatives has fueled the popularity of anthocyanin-enriched kefir, particularly through the incorporation of anthocyanin-rich sources such as black carrot, black mulberry, pomegranate, strawberry juice, blackberry, and blueberry extracts. These anthocyanin enrichments not only enhance the nutritional value but also introduce vibrant colors and health-promoting properties to kefir, catering to the growing consumer interest in functional foods. In addition to dairy-based kefir, anthocyanin-rich ingredients have been added to a variety of non-dairy fermented beverages, including kombucha, beer, hardaliye, honey wine, turnip juice, and kvass, in varying proportions. This incorporation of anthocyanins into non-dairy beverages offers a novel approach to beverage formulation, providing new avenues for food innovation and enhancing the appeal of fermented products in the health-conscious market.

Table 1 summarizes some of the anthocyanin-enriched fermented beverages developed by incorporating a range of anthocyanin-rich foods, such as black carrot, black mulberry, pomegranate, strawberry juice, blackberry, and blueberry extract, into both dairy and non-dairy fermented beverages. One particular study examined the impact of

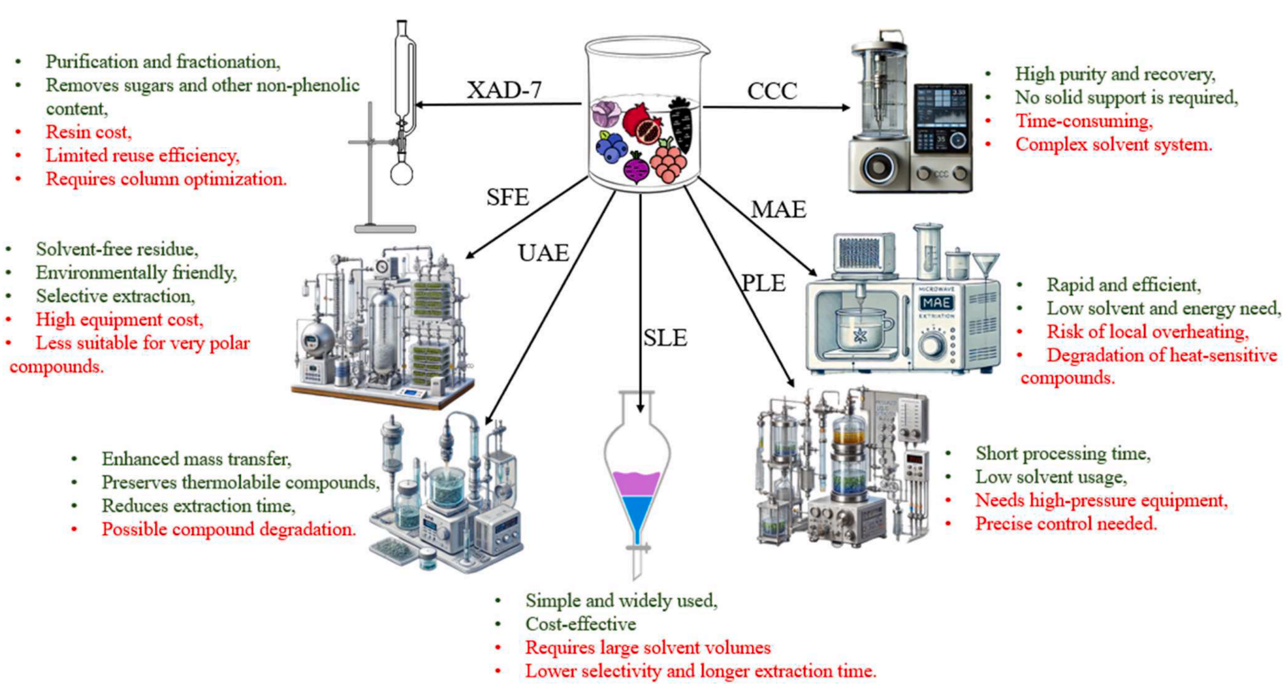

Fig. 3. Commonly used extraction techniques of anthocyanin (CCC: Countercurrent Chromatography, MAE: Microwave Assisted Extraction, PLE: Pressurized Liquid Extraction, SFE: Supercritical Fluid Extraction, SLE: Solid-Liquid Extraction, UAE:Ultrasound-Assisted Extraction) (Created from DALL-E and Freepik).

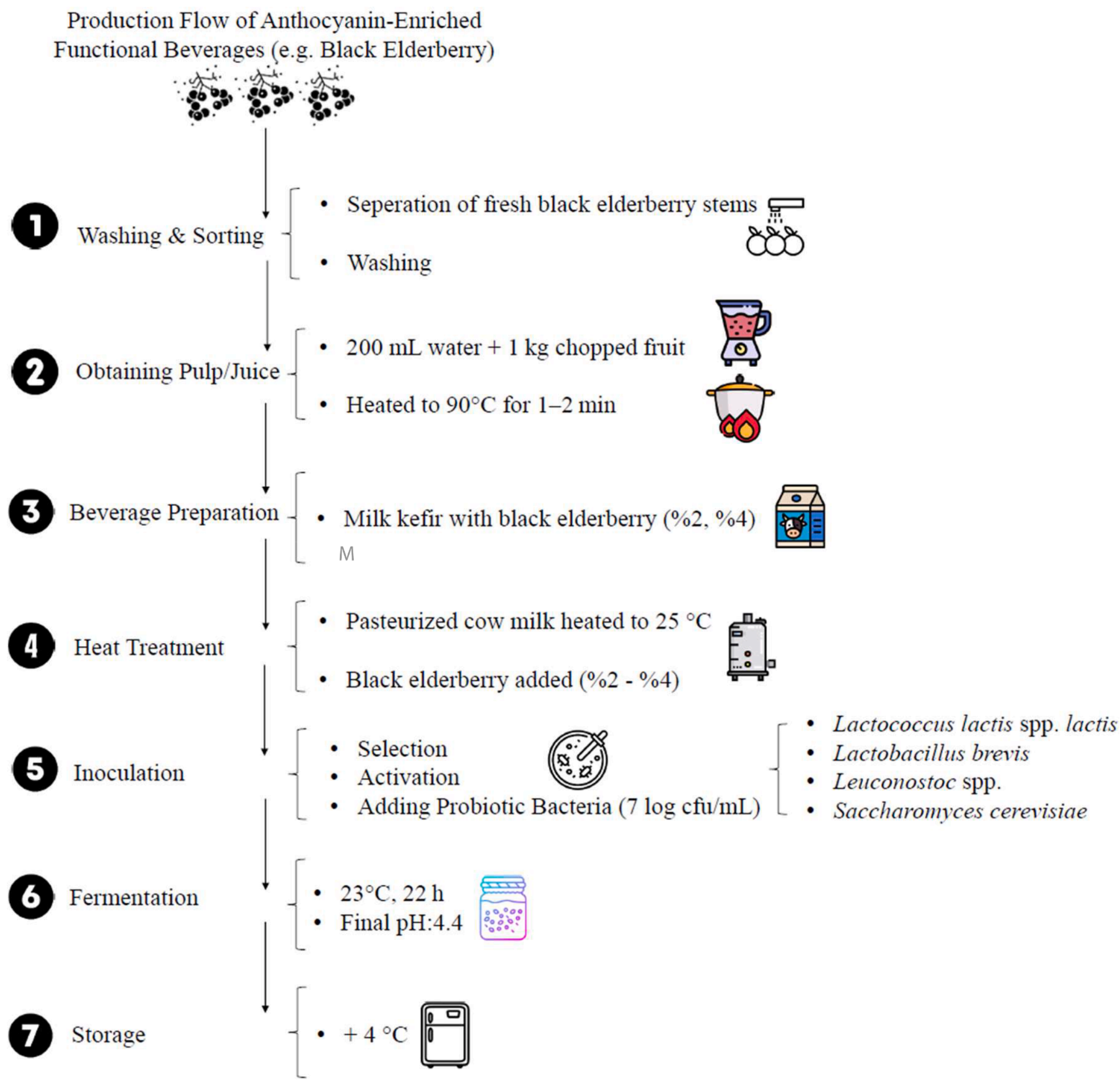

Fig. 4. Flow chart of the preparation of anthocyanin-rich fermented beverages i.e. with elderberry (CFU: colony forming unit) (Created from Freepik).

different proportions of processed fresh and dried elderberry powder on the properties of kefir beverages, both before and after fermentation. The results demonstrated that the total monomeric anthocyanin content in fresh elderberries was significantly higher than that of dried elderberries, highlighting the importance of raw material selection in maximizing anthocyanin content and enhancing the functional properties of the final product beverage (Dimidi et al., 2019). This research emphasizes the potential of using diverse anthocyanin-rich sources to further improve the health benefits and sensory qualities of fermented beverages, positioning them as valuable functional foods in modern dietary patterns.

Water kefir is a dairy-free probiotic beverage made by fermenting sugary water with water kefir grains, often enriched with fruits like dried figs or raisins, making it suitable for those with lactose intolerance. In contrast, milk kefir is a fermented dairy drink made from milk (cow, sheep, or goat) using kefir grains and contains lactose (Guzel-Seydim et al., 2021). A study by Esatbeyoglu et al. investigated the production of water kefir using *Aronia melanocarpa* juice and pomace, comparing the chemical, physical, and sensory properties (such as color, aroma, sweetness, acidity, and flavor) of the resulting beverages. The results revealed that water kefir made from aronia pomace exhibited a slower reduction in total phenolic content, total flavonoid content, and total anthocyanin content compared to the kefir made from aronia juice (Esatbeyoglu et al., 2023). This highlights the potential of using pomace, a by-product of fruit processing, to preserve bioactive compounds in fermented beverages, adding functional value to the final product.

Kombucha, another popular non-dairy fermented beverage, is traditionally prepared by fermenting sweetened tea leaves with a symbiotic consortium of yeasts and bacteria (Villarreal-Soto et al., 2018). Known for its rich content of bioactive compounds, kombucha offers numerous health-promoting benefits, including antibacterial, antihypertensive, anticarcinogenic, and antioxidant properties (Barakat et al., 2024). During fermentation and enrichment, kombucha beverages can become high in anthocyanins, further enhancing their functional and health-related properties, as detailed in Table 1 (Barakat et al., 2024; Caliskan et al., 2023; Ayed et al., 2017; Yildiz et al., 2020).

In a comparative study on the anthocyanin profiles in Şalgam, it was found that cyanidin-3-xylosyl-glucosyl-galactoside, acylated with ferulic acid, was the most abundant anthocyanin among other compounds present in the beverage. Additionally, research into kvass samples enriched with black chokeberry juice, sea buckthorn fruit juice, and peppermint leaves revealed valuable antioxidant properties. Notably,

Table 1
Advances in Anthocyanin-Enriched Fermented milk-based and non-dairy beverages.

Type of Beverage		Anthocyanin-Rich Food	Time	Main Outcomes	Cited
Dairy Beverages	Kefir	Black carrot (KBCJ), black mulberry (KBMJ), pomegranate (KPJ) and strawberry juices (KSJ) different concentrations (10%, 25%, 50% *w/v*)	12 weeks	-KBMJ showed the highest anthocyanin stability, followed by KPJ, KSJ, and KBCJ. -Fortification with 25% juices led to an increase (1.8-4.8 times) in antioxidant activity. -In sensory analyses, the most preferred concentrations among juices were 10% and 25%.	(Kabakcı et al., 2020)
		Encapsulated blackberry juice (EBJ) Different concentrations (1, 2.5, 5, and 7.5% *w/v*)	28 days	-EBJ greatly improved the antioxidant capabilities of kefir, depending on the fortification level. - Higher EBJ concentrations in kefir resulted in increased overall acceptance, -In the sensory evaluation, the most preferred samples by the panelists were the kefir containing 7.5% EBJ.	(Travičić et al., 2023)
		Black carrots (1% and 5%, *w/v*)	2 days	-Kefir containing 1% anthocyanin had a more balanced distribution of probiotic species, including *Lentilactobacillus kefiri* (17%), *Leuconostoc mesenteroides* (9%), and *Lactococcus lactis* (5%), with equal abundance rates. -The 5% anthocyanin kefir had the highest polarity in the community, with a substantial prevalence of probiotic *Lentilactobacillus* kefir (72%).	(Aydin et al., 2022)
		Blueberry extract and microalgae 0.5% of lyophilized microalgae, and 0.5% of blueberry extract	2 days	Anthocyanin (blueberry extract) addition to the kefir, reduced pathogenic bacteria, increased *Lentilactobacillus* and microbiota diversity.	(Aktas and Aydin, 2024)
		Fresh elderberry fruit mash (2% and 4%) and dried elderberry powder (0.5% and 1%)	14 days	-Kefir made with elderberry powder had a higher total phenolic content and antioxidant activity. -The highest ACE inhibitor activity was observed in the kefir sample with 1% dried elderberry supplement before fermentation on the first day of storage. -In the sensory evaluation, the effect of sample formulation on appearance and consistency was statistically significant ($p<0.05$).	(Barazi and Arslan, 2024)
	Probiotic Oat Beverage	Black chokeberry, red currant, blueberry, quince, Hawthorn fruit and whole sea buckthorn berries (100 g)	20 hours	-Antioxidant activity significantly decreased after 20 h of fermentation in all enriched oat beverages with no significant differences observed compared to control samples. -Fermented beverages had a high lactic acid bacteria count (> 8 log CFU/mL), a low pH (about 4.15), and no microbiological contamination.	(Marchwinska et al., 2023)
		Chokeberry berry juice (20%)	8 h	-As a result of the fermentation, antioxidant activity (DPPH and FRAP) was decreased. -In the sensory analysis, sensory acceptance of the beverage supplemented with 20% chokeberry juice increased (appearance, color, aroma, texture, flavor, sweetness, after taste)	(Yaneva et al., 2022)
Non-Dairy Beverages	Water kefir	*Aronia melanocarpa* juice (300 mL) and pomace (300 g)	2 days	Compared to water kefir made with aronia juice, samples made with aronia pomace showed higher TPC, TFC, and TAC.	(Esatbeyoglu et al., 2023)
	Kombucha	Grape pomace 100 g/L dry weight	10 days	-The phenolic profile of grape pomace improved at the end of fermentation, with an increase in TFC and TAC. -As a result of the fermentation, grape pomace kombucha had a higher antioxidant capacity, as well as antidiabetic and anti-inflammatory properties.	(Barakat et al., 2024)
		Aronia melanocarpa juice (10%) Green tea (14 g/L)	12 days	-The sample with green tea and aronia juice had the highest phenolic content. - The sample with green tea and aronia juice showed the maximum antioxidant potential in terms of extractable, hydrolyzable, and bioaccessible phenolics.	(Caliskan et al., 2023)
		Red grape juice 500 mL (10%)	12 days	-The phenolic and anthocyanin contents and antioxidant activity of the fermented beverage were approximately 2.47 and 1.59 times higher than the pre-fermentation values on the sixth day of fermentation. -In the sensory analyses, the taste panel gave the 6-day fermented juice an overall rating of acceptable after smelling and tasting. It had a good appearance and high acceptability, as opposed to the 12-day fermented juice, which had a vinegary taste.	(Ayed et al., 2017)
		Black carrot juice (10% and 20%) Green tea (14 g/L)	12 days	-Kombucha tea with the highest anthocyanin concentration and antioxidant capacity contained 20% black carrot juice.	(Yildiz et al., 2020)
	Plant-Based Beverage	Blackberry, strawberry, banana, guava, mango, cantaloupe and watermelon different concentrations (30% and 40%)	28 days	The plant-based beverage contained anthocyanin and synbiotic activity, was microbiologically safe and had high consumer acceptability.	(Palencia-Argel et al., 2024a)
	Hardaliye	Blue-black grape	60 days	-Malvidin-3-*O*-glucoside was found to be the most abundant anthocyanin, while hardaliye contains a significant concentration of resveratrol.	(Aşkın and Atik, 2016)

(*continued on next page*)

Table 1 (*continued*)

Type of Beverage	Anthocyanin-Rich Food	Time	Main Outcomes	Cited
			- The hardaliye contains a high total phenolic content and antioxidant activity.	
Şalgam	Black carrot	3 days	Cyanidin-3, xylosyl-glucosyl-galactoside acylated with ferulic acid was found to be higher than the other individual anthocyanins	(Tanguler et al., 2020)
Mead	*Hibiscus sabdariffa* and *Betula pendula* (Birch sap) and honey-birch sap	21 days	Delphinidin-3-*O*-sambubioside and cyanidin-3-*O*-sambubioside were found.	(Essiedu and Kovaleva, 2024)
Kvass	Black chokeberry juice (*Aronia melanocarpa*) 300 mL (3, 5, and 10%)	21 days	-Kvass containing 10% black chokeberry juice showed the strongest antioxidant activity. -Chromatographic analysis revealed that adding black chokeberry juice to kvass increased the concentration of 13 phenolic compounds (1.68-1.73 mg/100 mL)	(Kaszuba et al., 2024)
Fermented Beverage	Selenium (5 mg/L)	52 days	-This fermented and Se-bioenriched beverage showed acceptability and improved sensory attributes than the original non-fermented drink -It also shown great microbiological tolerance to stress factors including cold storage and digestive conditions.	(Martinez et al., 2024)
Antioxidant-Enriched Beverage	Grape musts and extracts of winery and grapevine by-products	3 days	The polyphenol-rich grape juice made from grape pomace, grapevine leaves, and canes has a promising Trolox equivalent antioxidant capacity of 77.2 mmol/kg.	(Aguilar et al., 2018)
	Black carrot and blueberry	1 day	- The highest mean values for TPC and TFC were found in the cider enriched with black carrot extract (0.3%, *v/v*) and blueberry extracts (5%, *v/v*) - The antioxidant performance indicators (FRAP and DPPH) were positively correlated with the TPC and TFC of the cider types. Cider with carrot addition, blueberry added (368.3, 243.3 mg gallic acid equivalent/L and black carrot addition (30.4; 25.7 mg quercetin equivalent/L)	(Brezan et al., 2020)
	Potatoes of purple-color flesh (21.34% dry matter content)	14 days	-Petunidin 3-(*p*-coumaroyl)-rutinoside-5-glucoside was detected -Beer samples showed increased antioxidant activity, higher concentration of anthocyanins. -Beer made with 30% purple potatoes showed acceptable organoleptic properties.	(Gasiński et al., 2023)

2,2-diphenyl-1-picrylhydrazyl (DPPH); Angiotensin-Converting Enzyme (ACE); Colony Forming Unit (CFU); Ferric-reducing Antioxidant Power Assay (FRAP); Gallic Acid Equivalent (GAE); Hibiscus sabdariffa (HS); Total Anthocyanin Content (TAC); Total Flavonoid Content (TFC); Total Phenolic Content (TPC).

kvass containing black chokeberry juice exhibited two distinct anthocyanins—cyanidin 3-O-glucoside (59.3–100.8 μg/100 mL) and cyanidin 3-O-galactoside (34.6–57.4 μg/100 mL), underscoring the rich anthocyanin content and antioxidant potential of this beverage (Tanguler et al., 2020; Kaszuba et al., 2024).

Furthermore, in the production of beer, another fermented beverage, a purple-fleshed potato variety rich in anthocyanins was incorporated into the brewing process. Beer made with a 30% purple potato addition contained a total anthocyanin concentration of 12,383 mg per dm^3, while beer with a 50% purple potato addition reached 36,507 mg per dm^3, highlighting the potential of using anthocyanin-rich plant sources to enhance the nutritional and functional profile of fermented beverages (Gasiński et al., 2023). This expanding variety of anthocyanin-enriched fermented beverages demonstrates the growing potential of these products to offer both enhanced sensory attributes and significant health benefits, offering new possibilities for functional food development.

4. Impact of anthocyanin-rich beverages on health

In recent years, fermented beverages have garnered increasing attention due to their health-promoting effects, particularly in mitigating inflammation and regulating oxidative stress (Durazzo et al., 2022). Research has indicated that the incorporation of *Bifidobacterium*, a beneficial bacterium commonly present in fermented foods, may alleviate excessive stress responses, prevent cognitive decline, and reduce the risk of neurodegenerative diseases (Alzheimer's and Parkinson Disease). Furthermore, *Bifidobacterium* has been found to support healthy levels of brain-derived neurotrophic factor (BDNF), a key protein often deficient in individuals suffering from depression. Moreover, studies have demonstrated that the addition of anthocyanins to kefir, at varying concentrations, effectively reduces the abundance of pathogenic bacteria while promoting the growth of *Lentilactobacillus* and enhancing the diversity of the microbiota. The incorporation of anthocyanins into kefir not only elevates its functional properties but also contributes to the creation of a more biodiverse kefir beverage, thus expanding its potential health benefits (Kabakcı et al., 2020; Aydin et al., 2022; Travičić et al., 2023; Aktas and Aydin, 2024).

Anthocyanins, recognized for their potent anti-inflammatory and antioxidant properties, are bioactive compounds that offer a wide array of health benefits. These include the potential to mitigate cellular and tissue damage, balance uric acid, protein, lipid and glucose metabolism, decrease the production of pro-inflammatory cytokines (IL-6, TNF-α), total cholesterol, LDL, triglyceride and liver enzyme levels, increase the HDL and contribute to overall homeostasis within the body (Mehmood et al., 2019; Bedê et al., 2020; Daskalova et al., 2021; Gadhoumi et al., 2025). Additionally, studies have shown that fermented products containing anthocyanins strongly inhibit α-amylase and α-glucosidase enzymes in serum samples (Gadhoumi et al., 2025). A critical aspect of their metabolism is their capacity to provide systemic protection against lipid peroxidation, particularly in the brain, while also reducing the activity of monoamine oxidase (MAO). This reduction in MAO activity can enhance the availability of neurotransmitters in synapses, which may support improved mental health and cognitive function (Rodríguez et al., 2021). Thus, the integration of anthocyanins into fermented beverages, such as kefir, not only enhances their nutritional value but also supports metabolic health, particularly in terms of neurological protection and stress management.

Figure 5 illustrates the potential health benefits associated with fermented anthocyanin-rich beverages, highlighting their bioactive properties and their impact on overall well-being. These beverages, rich in antioxidants and other phytochemicals, are shown to support various physiological functions, including enhanced cardiovascular health, improved cognitive function, and reduced oxidative stress. The figure also emphasizes their role in modulating gut microbiota, boosting

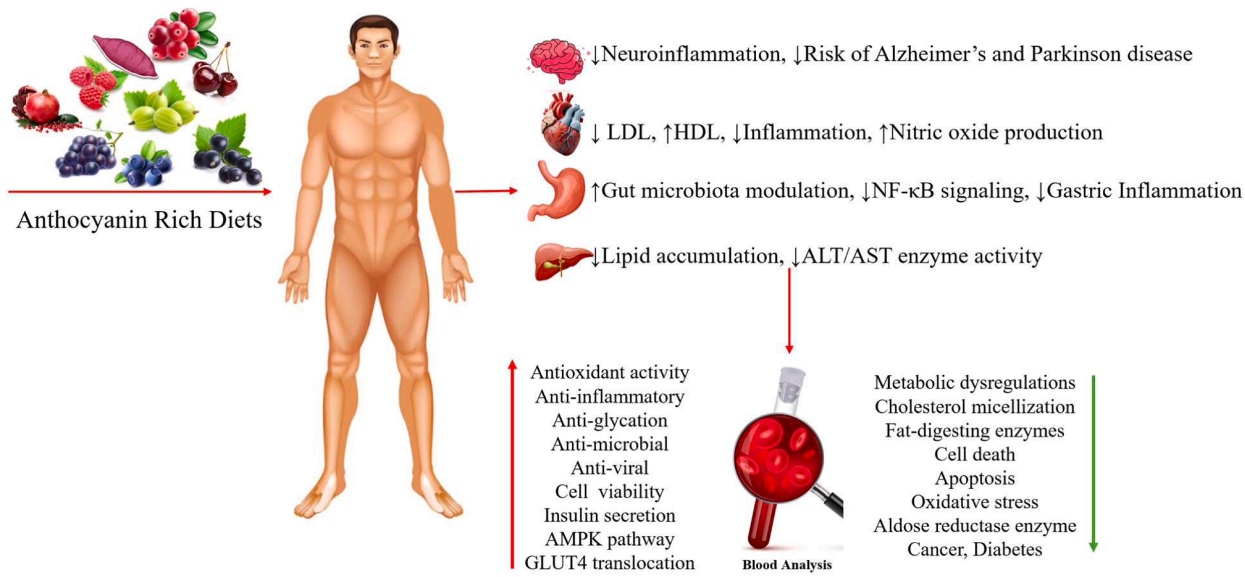

Fig. 5. Anthocyanin rich food has an impact on health (Chamnansilpa et al., 2020; Xiao et al., 2021; Yu et al., 2021; Filaferro et al., 2022; Li et al., 2022; Shu et al., 2022; Chen et al., 2022; Leonarski et al., 2024) (Created from Freepik).

immune responses, and mitigating the risk of important diseases such as type 2 diabetes (T2DM) and types of cancer (breast, colon and pancreatic). Fermented beverages containing anthocyanins, particularly in the form of delphinidin-3-arabinoside, show therapeutic potential in T2DM patients (Mistry et al., 2025). By suppressing one of the targeted enzymes, dipeptidyl peptidase-IV (DPP-IV), due to the phenolic compounds found in these beverages, the degradation of its substrate, glucagon-like peptide-1 (GLP-1), is reduced, thus the incretin effect is strengthened and glucose-stimulated insulin secretion from pancreatic β-cells is increased. Studies have shown that fermented products containing anthocyanins significantly increase GLP-1 gene expression. In addition, these products increase the levels of genes and proteins related to insulin signaling, especially insulin-like growth factor binding proteins (IGF-II, IGFBP-2 and IGFBP-3) and vascular endothelial growth factor (VEGF) (Johnson and De Mejia, 2016). The consumption of anthocyanin-rich foods, such as blackberries (Rubus sp.) and blueberries (Vaccinium sect. Cyanococcus), has been linked to positive health outcomes, including the slowing of the aging process and the modulation of inflammatory responses (Li et al., 2017; Zhang et al., 2019). A key reason for the anti-inflammatory and cell health benefits of anthocyanins is their ability to inhibit critical cellular signaling pathways, including the Nuclear Factor-κB (NF-κB) pathway, the activated phosphatidylinositol 3-kinase/Protein kinase B (PI3K/AKT) pathway, and AMP-activated protein kinase (AMPK) signaling in glucose metabolism (Castaldo et al., 2021; Mi et al., 2024). Moreover, it may offer new targets for the dietary management of cancer, obesity, T2DM, and its complications by promoting both mitochondrial function and density by enabling translocation of GLUT4 in both skeletal muscles and adipose tissues through upregulation of AMPK and restoration of insulin sensitivity (Solverson, 2020). However, by blocking these pathways, anthocyanins significantly reduce the production of inflammatory cytokines, which are known to exacerbate tissue damage during inflammatory responses. This anti-inflammatory mechanism not only protects cells but also highlights the potential of anthocyanins in managing various inflammatory conditions more effectively (Bedê et al., 2020). As depicted in Figure 5, anthocyanins possess a diverse range of bioactive properties, including antidiabetic, anticancer, anti-inflammatory, antimicrobial, and anti-obesity effects. Furthermore, their consumption has been shown to provide substantial protective benefits against several chronic health conditions, such as cardiovascular diseases, neurodegenerative diseases, cancer, T2DM, and atherosclerosis (Durazzo et al., 2022; Mattioli et al., 2020). These compelling health-promoting effects underscore the therapeutic potential of anthocyanin-enriched fermented beverages, which can play a critical role in supporting overall well-being and mitigating the risk of chronic diseases.

The anti-inflammatory effects of anthocyanins have been demonstrated through various in vitro assays, highlighting their potential in reducing nitric oxide (NO) production. Specifically, cyanidin-3-*O*-glucoside reduced NO production by 59.5% to 13.5%. Additionally, prostaglandin E (PGE) downregulation from 87% to 10.4% was observed in activated macrophages, indicating significant anti-inflammatory effects. Another study has investigated the role of anthocyanins in mitigating oxidative stress. The findings revealed that individuals consuming anthocyanin-rich beverages exhibited increased activities of antioxidant enzymes, including superoxide dismutase and catalase, which are crucial in neutralizing free radicals. This suggests that anthocyanins have the potential to prevent oxidative damage. Plasma antioxidant capacity was significantly elevated due to anthocyanin consumption, while levels of malondialdehyde, a marker of oxidative stress, decreased substantially (Kuntz et al., 2014).

Recent evidence further supports the beneficial role of anthocyanins in modulating gut microbiota composition. Studies have shown that anthocyanins can inhibit the growth of a variety of pathogenic bacteria, including Gram-negative species such as *Citrobacter freundii, Escherichia coli, Pseudomonas aeruginosa*, and *Salmonella enterica* ser. *typhimurium*, as well as Gram-positive species such as *Listeria monocytogenes, Staphylococcus aureus, Bacillus subtilis*, and *Enterococcus faecalis* (Yang and Kortesniemi, 2015; Jamar et al., 2017; Lavefve et al., 2020). Importantly, anthocyanins do not inhibit the growth of beneficial microorganisms like *Bifidobacterium* and *Lentilactobacillus* species. These beneficial bacteria can metabolize anthocyanins into bioavailable molecules, such as phenolic acids, which may possess even greater biological activity, thereby enhancing the overall health benefits of anthocyanins (Danneskiold-Samsøe et al., 2019; Palencia-Argel et al., 2024b).

These findings underscore the multifaceted therapeutic properties of anthocyanins, suggesting their significant role in promoting gut health, reducing inflammation, and mitigating oxidative stress, thereby contributing to overall health improvement.

5. Conclusion and Future Directions

This study highlights the transformative potential of anthocyanin-rich fermented beverages as functional foods, emphasizing their remarkable health benefits, including antioxidant, anti-inflammatory, antimicrobial, and gut-modulating effects. By leveraging advanced fermentation processes, these beverages achieve enhanced nutritional value, improved bioavailability of anthocyanins, and superior sensory qualities. The findings demonstrate their capacity to support cardiovascular health, cognitive function, and metabolic balance while offering resilience against chronic conditions such as T2DM, cancer, and neurodegenerative disorders.

Future research should prioritize the optimization of production technologies of anthocyanin-enriched fermented beverages to improve scalability and cost-effectiveness while maintaining bioactive compound stability. Innovative approaches, such as combining anthocyanins with other bioactive compounds, could lead to synergistic health effects, paving the way for the development of multifunctional beverages targeted at specific health needs. Moreover, exploring underutilized anthocyanin-rich plant sources and incorporating sustainable production practices can further expand the diversity and ecological footprint of these products. Current studies should focus on various strategies including combining functional components in a synergistic approach, utilizing distinctive microbial species that may improve anthocyanin bioavailability, creating consumer-friendly formulations, and using production techniques that put environmental sustainability first when producing fermented products with anthocyanin content.

To deepen scientific understanding, future studies should investigate the molecular mechanisms underlying the health benefits of anthocyanins, including their interactions with gut microbiota and their role in modulating key biochemical pathways. Conducting long-term clinical trials will also be essential to substantiate their therapeutic potential and provide evidence-based dietary recommendations. Furthermore, in accordance with consumer preferences, features such as the flavor profile, cultural popularity, and packaging design of these products should be taken into consideration; they should be backed up by market research and sensory assessments. Functional beverages high in anthocyanins stand out as a cutting-edge solution area that will promote personal health and assist sustainable food systems. In this regard, further mechanistic and long-term clinical research could influence the global market for functional beverages by putting these products' therapeutic potential on a stronger scientific foundation.

Consumer acceptance and market analysis should accompany these advancements to ensure that anthocyanin-rich fermented beverages align with global consumer preferences and dietary trends. This includes studying sensory attributes, cultural influences, and packaging innovations to make these products more appealing and accessible.

By addressing these challenges and leveraging the insights gained from this study, the field of anthocyanin-enriched fermented beverages can significantly contribute to public health and the sustainable growth of the functional beverage industry. This research not only sets the foundation for future innovations but also underscores the importance of integrating science, technology, and sustainability to deliver health-promoting solutions to consumers worldwide.

Ethical statement

This work does not involve animal or human studies for experimentation.

Ethical Statement - Studies in humans and animals: Not applicable for our submission. We are submitting a review article

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CRediT authorship contribution statement

Büşra Yusufoğlu: Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Yasemin Açar:** Writing – review & editing, Writing – original draft, Data curation. **Gizem Kezer:** Writing – review & editing, Writing – original draft, Data curation. **Sina Zargarchi:** Writing – review & editing, Data curation. **Kerem Mertoglu:** Writing – review & editing, Investigation. **Tuba Esatbeyoglu:** Writing – review & editing, Project administration, Funding acquisition, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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