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Sustainable Recovery of Anthocyanin from Purple Cabbage and Their Functional Role in Food Systems

Nithya R[1], Sangeetha Baskaran[1*]
[1]*Department of Biotechnology, St. Joseph's College of Engineering, OMR, Chennai, Tamil Nadu, India.*

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ABSTRACT
Anthocyanins are natural flavonoid pigments that have been widely investigated as sustainable substitutes of synthetic food colorants because of their coloration capacity and bioactivity. Purple cabbage (Brassica oleracea var. capitata f. rubra) is a cheap and rich source of anthocyanins that are primarily cyanidin derivatives. This review provides the critical analysis of recent developments in the sustainable extraction of anthocyanins in purple cabbage with specific focus on the green methods of extraction such as ultrasound-based, microwave-based, and enzyme-based extraction. The impact of important processing factors (solvent composition, pH, temperature and extraction time) on yield and efficiency is discussed systematically. Besides, the anthocyanins stability in various environmental conditions and the methods of improving their stability such as encapsulation and co-pigmentation are also considered. The practical usage of these pigments in food systems is also outlined, which emphasizes their usage as natural colorants, antioxidants and pH-responsive indicators in different food systems. Although they have a promising potential, the issues of stability and large-scale processing are crucial setbacks. The review presents an understanding of outstanding sustainable extraction methods and the future expectations of the efficient use of purple cabbage anthocyanins in the value-added production of clean-label and functional food products.
Keywords: Anthocyanins, Purple cabbage, Green extraction, Stability, Natural food colorants, Functional food systems

I. INTRODUCTION

The growing consumer preference towards the use of natural, safe, and sustainable food ingredients is a major factor that has drastically prompted the substitution of synthetic food additives with plant-based food additives in the food industry. The widespread uses of synthetic food colorants, which are low-cost, stable, and highly coloured, have also been linked to the possible negative health effects, including allergic reactions and behaviouralchanges, and cause concern among consumers and regulatory bodies [1]. The global food industry is responding to this by a shift in the paradigm where clean-label food is being adopted in the food industry, where natural and minimally processed foods are the main focus. It has also boosted studies on naturally occurring pigments, especially those with both a colouring effect and functional and health-promoting properties [2].

Anthocyanins are considered one of the most promising classes of compounds among the natural pigments because of their colourful colouration, solubility in water and broad distribution throughout plant tissues. Anthocyanins are polyphenolic flavonoid compounds responsible for red, purple, and blue colour of many fruits, vegetables, and flowers [3]. Their chemical structures are glycosides of anthocyanidins and are defined by the structure of flavylium cation, which is highly sensitive to the environmental factors of pH, temperature, light, and oxygen [4]. Besides colouring activities, anthocyanins also have numerous biological activities, such as anti-oxidant, anti-inflammatory, and anti-diabetic and anti-carcinogenic effects, and thus are useful as functional ingredients in food systems [5].

The use of anthocyanins in food industry is limited by anthocyanin instability despite its great potential. Structural degradation and loss of colour can result due to changes in pH, thermal processing, light exposure, and oxygen thus affecting their usefulness in food matrices [6]. Therefore, enhancing the extraction ability and stability of anthocyanins has attracted a lot of research in the present context. The recovery techniques should be efficient to ensure that the yield is maximized with an additional consideration of maintaining the structural integrity and bioactivity of these compounds.

Much attention has been paid to purple cabbage (Brassica oleracea var. capitata f. rubra) as a source of anthocyanins that is economical and sustainable. It contains acylated anthocyanin

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derivatives, predominantly cyanidin derivatives, that are unusually stable compared to those that are not acylated because of intramolecular co-pigmentation effects [7]. Purple cabbage is an appealing source of anthocyanin since it is a high-pigment cost-effective crop readily grown on a large scale due to the high concentration of the biochemical and its easy accessibility. Moreover, the fact that the agricultural by-products and the waste used in the processing of purple cabbage are used in accordance with the principle of sustainable development as they decrease the waste and encourage more efficient use of resources.

The most common traditional ways of extracting anthocyanins are solvent extraction with water, ethanol, or methanol, which is usually acidified to preserve the flavylium form of anthocyanins [8]. Although these techniques are easy and highly utilized, they are commonly linked with the disadvantages that include long extraction duration, large-scale consumption of solvents, and possible degradation of heat-sensitive substances. Over the last years, there was the increasing stress on the creation of the more efficient, environmentally friendly, and sustainable green extraction technologies. Such methods include ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and enzyme-assisted extraction (EAE) which have shown high levels of enhancement in the extraction efficiency, less processing time, and less use of solvents [9]. These modern techniques increase the transfer of mass, break the walls of the plant cells and release the intracellular compounds hence yielding anthocyanin.

Besides extraction, other important issues of anthocyanins in food systems are the stability of anthocyanins to enhance their use in food systems. Several approaches such as encapsulation, co-pigmentation and the use of stabilizing agents have been studied to give them resistance to environmental stressors [10]. Encapsulation methods and microencapsulation and nanoencapsulation have demonstrated encouraging outcomes in the resistance of anthocyanins to degradation and preserving their bioavailability and activity. Further, the use of anthocyanins in food systems as natural colourants, antioxidants and pH sensitive indicators have gained growing interest, especially in the production of functional foods and intelligent packaging systems.

In the face of such developments, there is a necessity to have an overall idea of sustainable methods of extraction and how anthocyanins that are obtained after the extraction of purple cabbage can be functional in food systems. This review, thus, is an attempt to critically analyse the existing extraction methods, aspects that influence the extraction efficiency and measures that can be taken to improve the stability of anthocyanins. These pigments are also explained as regards to their usage in several food products and the health benefits that are associated with these pigments. Lastly, the problems and prospects that are linked to the industrial use of purple cabbage anthocyanins are brought out which gives information on how further research and development to be conducted in the area.

II. ANTHOCYANINS: STRUCTURE, CLASSIFICATION AND PROPERTIES

Anthocyanins are a family of water-soluble pigments that are naturally present as flavonoid molecules in the polyphenolic organophosphate family. They are commonly found in tissues of plants and mainly cause the observed red, purple and blue colour in most fruits, vegetables and flowers. Anthocyanins in plants have various biological roles such as environmental stress protection, pollinator attraction and protection against ultraviolet radiation [11].

Anthocyanins are structurally glycosylated forms of anthocyanidins, which are derived off of anthocyanidins, which are anchored on a flavylium cation (2-phenylbenzopyrylium) backbone. This central framework comprises of two aromatic rings (A and B) coupled together by heterocyclic pyran ring (C), which makes a C6-C3-C6 framework. The structural diversity of anthocyanins is brought about by difference in patterns of hydroxylation, methylation, glycosylation, and acylation, which largely determine their colour, stability as well as the chemical behaviour [12].

Anthocyanins are generally distinguished according to the nature of anthocyanidin aglycone and nature of the attached sugar moieties. There are six principal anthocyanidins, namely cyanidin, delphinidin, pelargonidin, peonidin, petunidin and malvidin. The colour of the pigment depends on the number and location of hydroxyl and methoxy groups on the B-ring, and as the percentage of hydroxyl groups increases to produce a bluish colour, and the percentage of methoxy groups increases to produce a redder colour. The glycosylation is usually done at the C3 position, which enhances aqueous solubility and stability [13].The structure of anthocyanin is shown in Figure.1.

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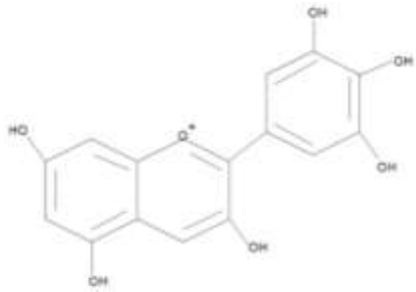

Figure1: Structure of Anthocyanins

The sensitivity of anthocyanins to pH is also one of the most peculiar physicochemical characteristics. They experience reversible structural changes with regard to acidity or alkalinity of the medium. When acidic the flavylium cation will be dominant which gives it a red coloration. Also the anthocyanins as the pH is raised change into other forms of the molecule, the colourless carbinol pseudo base and chalcone and the blue-coloured quinoidal base. These structural modifications are regulated by multifaceted equilibria and are important in the determination of the colour and stability of anthocyanins in food systems [14].

Environmental factors including temperature, light, oxygen and enzymatic activity also affect anthocyanins. Their chemical structure renders them vulnerable to degradation by hydrolysis reactions, oxidation reactions, and polymerization reactions. The result of these processes may include loss of colour and bioactive properties, making their use in food products difficult. The degradation rate is determined by intrinsic (the molecular structure and the extent of acylation) and extrinsic (storage and processing conditions) factors [11].

Besides the colouring properties, anthocyanins also possess a considerable functional property especially in their antioxidant activity. The presence of hydroxyl groups on the aromatic rings of these compounds helps them to scavenge free radical and inhibit oxidative reactions. This anti-oxidant potential is part of their contribution towards health promotion and prevention of oxidative stress related diseases [13].

III. PURPLE CABBAGE AS A SOURCE OF ANTHOCYANINS

Purple cabbage (Brassica oleracea var. capitata f. rubra) is a significant cruciferous vegetable noted to be rich in natural pigments especially anthocyanins, which give it its characteristic rich purple hue. Its high phytochemical content, simplicity in production, and availability throughout the year, has focused a lot of interest in it as a possible source of natural food colorants [15,16].

Besides anthocyanins, purple cabbage is also a good source of diverse bioactive compounds including glucosinolates, phenolic acids, vitamins, and minerals, which improve its health and nutritional properties.

Purple cabbage anthocyanin profile is mainly composed of cyanidin-based anthocyanins with a high level of acylation by aromatic acids. Such acylated hairs enable greater molecular stability via an intramolecular co-pigmentation mechanism, and anthocyanins of purple cabbage are more resistant to degradation than most other plant sources [17].

The added stability is also of great benefit especially where they are to be used in the food system where exposure to different environmental conditions may severely impact pigment integrity.The different sources of anthocyanins are shown in Figure. 2.

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Figure 2: Different sources of Anthocyanin

Anthocyanins concentration and composition depend on a number of intrinsic and extrinsic factors such as genetic variation, agronomic practices, environmental factors and post-harvest storage of purple cabbage. The exposure to light, such as in anthocyanin synthesis, is influenced by the light intensity with the high light intensity encouraging the pigment stocking in the outermost leaves [18]. Equally, changes in temperature and nutrient status can influence the metabolic pathways which participated in the production of anthocyanins, which in turn impacts on the total yield and quality.Technologically, the purple cabbage has a number of benefits which include use in the extraction of anthocyanin as a raw material. Its moisture content is relatively high, which is why it is easy to extract solvents, whereas its soft tissue structure makes it easy to release intracellular pigments [19].

Additionally, the processing by-products, including outer leaves and cut off wastes offer an opportunity to obtain pigments based on cost-effective methods of recovery and contribute to sustainable waste management practices in the food industry.Functionally speaking there have been various studies on the functionality of the anthocyanin in purple cabbage as natural food colorants and functional ingredient. High antioxidant activity helps in extended shelf-life and nutritional value of food stuff and their colour properties are pH-sensitive which allows their use in intelligent packaging system to monitor the freshness of food [20].

Such versatile characteristics render purple cabbage a promising ingredient of inclusion in diverse foodstuff groups, such as drinks, dairy products, and candy products.Although it has its strengths, there are some obstacles coupled with the act of using purple cabbage as the source of anthocyanins. The composition of the pigments, their degradation properties due to the conditions of the processing process, and possible interaction with other food substance can influence the consistency and performance of the extracted pigments [21].

IV. EXTRACTION OF ANTHOCYANINS FROM PURPLE CABBAGE

Anthocyanins in purple cabbage (Brassica oleracea var. capitata f. rubra) are usually extracted with polar solvents including methanol, ethanol and water or the acid form of these solvents in order to increase the stability and solubility of the pigment. Traditional solvent extraction is still very popular because of its simplicity but nonetheless, in many instances it takes a longer time to extract and more solvent is used.

To address these shortcomings, more sophisticated methods like ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) have been developed that are beneficial in terms of mass transfer and less time to take, as well as yield. The choice of extraction method is based on the factors like the required yield, cost, environmental effects, and scalability, and green extraction methods are being progressively considered due to their sustainability and efficiency [23, 24].Figure. 3 illustrates the extraction of anthocyanin from purple cabbage.

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Figure. 3: Extraction of anthocyanin from purple cabbage

4.1Conventional Extraction Methods

Conventional methods used in the extraction of anthocyanins are usually solvent-based involving the use of water, methanol, ethanol, their combinations, acidified usually with organic acids like hydrochloric or citric acid to ensure the anthocyanins remain in the flavylium cation form. Ethanol acidified is a relatively low toxicity material that is generally favoured because it can be used in food purposes [22].

One of the most common and least complex techniques is called Maceration, where the plant material is immersed in solvent over a long duration in order to induce the diffusion of pigments. Nevertheless, this technique comes with some drawbacks that include the fact that it takes long extraction time, a lot of solvents are used, and the possibility of degrading thermolabile compounds. Soxhlet extraction is more effective than the process of maceration, but it entails continuous heating, so anthocyanin can be damaged by the exposure to high temperatures [23].

4.2Ultrasound-Assisted Extraction (UAE)

Extraction by ultrasound with assistance has proved to be an effective green method of extraction that promotes the use of acoustic cavitation to extract anthocyanins. Microbubble formation and breakage also destabilize the walls of the plant cells, enhancing the penetrations of solvents and the transfer of mass [24].

UAE has a number of benefits which include less time of extraction, less solvents and higher extraction yield than the traditional ones. Moreover, it works at comparatively low temperatures, and this preserves anthocyanins that are sensitive to heat. The ultrasonic power, extraction time and solvent composition are parameters that need to be optimized to realize maximum efficiency [25].

4.3Microwave-Assisted Extraction (MAE)

Microwave-Assisted Extraction (MAE) MAE is a microwave technique of extracting natural or aquatic resources using microwave energy. Microwave-assisted extraction employs a set of microwave energy, which heats the solvent and plant matrix quickly and causes cell rupture and release of intracellular compounds. The method saves a lot of time in extraction and increases the efficiency of extraction [26].

The benefits of MAE are homogeneous heating, lesser usage of solvents, and increased yield of extraction. Nevertheless, too much microwave energy or long exposure can cause anthocyanins degradation and therefore processing conditions must be optimized [27].

4.4Enzyme-Assisted Extraction (EAE)

Enzyme-Assisted Extraction (EAE) is a technique employed to extract cellular proteins via the use of enzymes. Enzyme-assisted extraction is a technique that uses cell wall-degrading enzymes like cellulase, pectinase and hemicellulose to distort the structures of plant cells and release anthocyanins. The approach is efficient in extraction and works under mild conditions and thus maintains the structural integrity of bioactive compounds. EAE can be viewed as one of the environmentally friendly processes because it consumes little energy and uses a little solvent. Nonetheless, enzyme concentration, incubation time, temperature, and pH have to be strictly regulated in order to attain the best results [28].

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4.5Pressurized Liquid Extraction (PLE)

Accelerated solvent extraction is also referred to as pressurized liquid extraction, which is a technique that applies high pressure and moderate temperatures in order to improve solvent penetration and solvent extraction. The method can be used to extract within a short time with minimum use of solvents and high recovery rate. PLE can be used under controlled conditions is especially beneficial in extraction of anthocyanins, since it reduces degradation and enhances reproducibility [29].

4.6Factors Affecting Extraction Efficiency

Some of the parameters affecting the efficiency of anthocyanin extraction are solvent type, pH, temperature, extraction time and solid to liquid ratio. Ethanol and water are usually more suitable in extracting anthocyanin because it is compatible with the solvents because they are hydrophilic in nature. The pH is important in the stabilization of the anthocyanins in the extraction process and the acidic environment supports the formation of the stable flavylium cation. Temperature has the ability to increase extraction kinetics, however it should be well regulated to avoid thermal degradation. In the same way, the yield may be enhanced by increasing the extraction time until a point, and thereafter, degradation may set in [30].

4.7.Comparison of Extraction Techniques

The superior performance of the advanced extraction techniques like UAE, MAE, and EAE has been observed as a better extraction yield, time-saving process, and environmental sustainability,relative to the traditional extraction techniques. Although older techniques are still popular because of their ease of use and low expense, green extraction technologies are becoming more popular when it comes to industrial usage since they offer ease in terms of energy consumption and decrease in solvent content, compared to old techniques, with high-quality extracts [31].

Table 1: Comparison of Extraction Techniques for Anthocyanins

Extraction Method	Principle	Advantages	Limitations	Reference
Conventional Solvent Extraction	Uses polar solvents (ethanol, methanol, water) to dissolve anthocyanins	Simple, cost-effective, widely used	Time-consuming, high solvent use, degradation risk	[23]
Soxhlet Extraction	Continuous hot solvent extraction	Efficient extraction	High temperature may degrade anthocyanins	[22]
Ultrasound-Assisted Extraction (UAE)	Cavitation breaks cell walls	Faster, higher yield, less solvent	Equipment cost, optimization needed	[24]
Microwave-Assisted Extraction (MAE)	Microwave heating enhances extraction	Rapid extraction, reduced solvent use	Risk of thermal degradation	[26]
Enzyme-Assisted Extraction (EAE)	Enzymes degrade cell wall components	Eco-friendly, improved yield	Cost of enzymes, longer processing	[28]
Pressurized Liquid Extraction (PLE)	High pressure improves solvent penetration	Fast, efficient, reproducible	Expensive equipment	[29]

V. STABILITY OF ANTHOCYANINS

The structural integrity of anthocyanins remains a pivotal determinant of their functional utility in food matrices. While valued for their vivid pigmentation and nutraceutical benefits, these molecules exhibit high susceptibility to exogenous stressors, which often results in chromophore breakdown and diminished biological efficacy.The long-term viability of cabbage-derived pigments is largely dictated by their response to processing environments. Their inherent molecular fragility under varying conditions can trigger unwanted bathochromic shifts and the compromise of their antioxidant potential [47].

5.1Effect of pH on Anthocyanin Stability

One of the strongest factors which influence the stability of anthocyanin and colour expression is pH. The anthocyanin displays structural changes that vary with the pH of the medium. At extremely acidic pH (smaller than 3), they occur as the stable flavylium cation, giving them a red colour. With rise in pH the structure changes to less stable forms like carbinol pseudo base and chalcone and the colour either fades or discolours [32].

In neutral and alkaline pH conditions anthocyanins are changed to quinoidal bases and give bluish and greenish colour. These forms are, however, less stable and easily degraded. This pH-sensitive property greatly constrains the application of anthocyanins to foods with neutral or alkaline pH but allows their use as a naturally occurring pH sensor in intelligent packaging systems [12].

5.2Effect of Temperature

The temperature is a significant factor in the kinetics of anthocyanins degradation. Higher temperatures increase the rate of chemical reactions e.g. hydrolysis, oxidation, polymerization, causing the breakdown of the anthocyanin molecules and the colour intensity to fade [33].

Methods of thermal processing like pasteurization and sterilization which are often applied in the food industry can greatly decrease the anthocyanin content. High temperatures usually degrade anthocyanins causing the production of brown pigments and other degradation products, which adversely impact the visual value and nutritional value of food products. Thus, to ensure anthocyanin stability, low processing temperatures, and low heat exposure are necessary [6].

5.3Effect of Light Exposure

Exposure to light, especially the ultraviolet (UV) and visible light can cause photodegradation of anthocyanins. Absorption of the light energy may cause oxidative reactions causing the breakdown of the flavylium structure and colour loss. The photodegradation is variable with the intensity of light, wavelength and exposure time. Light-protective packaging materials can have a significant effect in preservation of anthocyanins in food products. This is of great significance especially in beverages and other transparent products where exposure to light can never be avoided [34].

5.4 Effect of Oxygen and Oxidation

Oxygen has an anti-corrosive effect and oxidation has a pro-corrosive effect. Oxygen is an important factor in the degradation of Anthocyanin by oxidative reactions. Dissolved oxygen in food systems may also result in the emergence of reactive oxygen species (ROS) that may damage the anthocyanin structure leading to pigment degradation .Anthocyanin degradation can also be increased by enzymatic oxidation that can be catalysed by enzymes like polyphenol oxidase (PPO) and peroxidase (POD). Oxidative degradation could be controlled by limiting oxygen access via vacuum-packaging or creating an inert gas atmosphere or by incorporation of antioxidants to enhance pigment stability [35].

5.5Effect of Metal Ions

Anthocyanins are metal-binding ions like iron, copper and aluminium, and with their presence, the colour and stability of anthocyanin-complex can change. Although certain metal complexes can improve colour intensity, there are those that can catalyse oxidative reactions and stimulate degradation. The presence of trace metals in food systems may thus cause both positive and negative effects on food systems relative to their concentration, and interaction with anthocyanins. The metal ions are normally bound by Chelating agents so as to reduce the adverse effect they have on pigment stability [36].

5.6Co-pigmentation and Molecular Interactions

Another relevant process is co-pigmentation which amplifies stabilities of anthocyanins and colouring. It is an interplay between anthocyanins and other molecules like flavonoids, phenolic acids, alkaloids or metal ions resulting in the formation of stable complexes. Such reactions lead to more colour strength (hyperchromic effect) and wavelength change (bathochromic shift), enhancing visual attractiveness and stability of anthocyanin-containing products. The utilization of co-pigmentation in food formulations to improve the operations of natural colourants is very popular [37].

5.7Stability Enhancement Techniques

Encapsulation. Encapsulation has proved to be one of the best approaches to enhance stability of anthocyanin. Spray drying, freeze drying, liposomalencapsulation, and nanoencapsulation are some of the methods that involve the use of a protective matrix to ensure that anthocyanins are not exposed to environmental stressors. Leaving anthocyanins encapsulated promotes not only stability, but also solubility, bioavailability and controlled release of anthocyanins in food systems. Protective coats around anthocyanin molecules are usually made with wall materials like maltodextrin, gum Arabic and proteins [38].

5.8Shelf-Life and Conditions of storage

The stability and shelf-life of anthocyanins is greatly affected by the storage conditions such as temperature, light exposure, and the packaging environment. Storage under refrigeration as well as the avoidance of light and oxygen that lead to degradation is necessary. Stability can also be improved by use of proper packaging materials like non transparent or UV covering containers. Also, storing in an acidic environment can be used to keep the flavylium form and extend the colour retention [39].

Table 2: Factors Affecting Stability of Anthocyanins

Factor	Effect on Anthocyanins	Outcome in Food Systems	Reference
pH	Structural transformation of anthocyanins	Colour changes (red → blue)	[32]
Temperature	Accelerates degradation reactions	Loss of colour and bioactivity	[6]
Light	Causes photodegradation	Fading of colour	[34]
Oxygen	Promotes oxidation reactions	Pigment breakdown	[35]
Metal Ions	Complex formation or catalytic degradation	Colour instability or enhancement	[36]
Co-pigmentation	Molecular interaction with phenolics	Increased colour intensity and stability	[3]

VI. APPLICATIONS OF ANTHOCYANINS IN FOOD SYSTEMS

The anthocyanins have received significant interests in the food industry because they are natural colorants and natural bioactive compounds. This is because their capacity to confer bright colours, as well as health-promoting attributes, makes them useful components in the formulation of clean-label and functional food products. Anthocyanins use in plant-based sources, including the purple cabbage, has been witnessed to gain widespread application in all types of food systems in recent years [46].

6.1Natural Food Colorants

The anthocyanins have one of the main uses as natural food colorants. These have been broadly marketed to substitute synthetic dyes in a variety of products, which include beverages, confectionary, dairy products, and bakery product. The anthocyanins also offer red, purple, and blue colours based on the pH of the food, and this makes them very versatile. They are also more applicable as they are water soluble and are compatible with the aqueous food systems. Nevertheless, the stability of colours is a problem especially with products that are subject to different environmental factors. This notwithstanding, the growing

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consumer preference to natural ingredients has fuelled the continued adoption of natural ingredients in the food industry [40].

6.2Functional and Nutraceutical Ingredients

The antioxidant and health promoting values of anthocyanins have allowed them to be extensively used in functional foods. They help to mitigate oxidative stress and have been linked with possible effects of better cardiovascular results, anti-inflammatory effects and management of glycaemic levels. Anthocyanins present in food products like juices, yogurts, and dietary supplements also increase the nutritional value of these products. Their application as nutraceutical ingredients is in line with the increased demand of food products with extra health advantages over simple food [41].

6.3Application in Beverages

Beverages constitute one of the biggest uses of anthocyanin. They find application in fruit juices, soft drinks, sports drinks and alcoholic beverages to beautify the appearance and nutrition content. The anthocyanins colour change based on the pH is most appropriate in acidic drinks where they are more stable. Anthocyanins also enhance the functional profile of beverages rendering their antioxidant capacity in addition to coloration. There are however challenges like degradation during storage and interacting with other ingredients that should be well managed to make sure the products are of quality [42].

6.4Application in Dairy and Bakery Products

The anthocyanins have also been researched to be used in the dairy and bakery products. Anthocyanins are also used as natural colorants in the dairy system like yogurt and flavoured milk besides improving antioxidant activities. Nevertheless, they can be affected by interactions with proteins and the change in pH that can affect their stability and colour expression. Anthocyanins are employed to impart natural coloration in bakery products but they are unstable in high baking temperatures. Thus, encapsulation methods have been widely used to preserve anthocyanins during thermal processing and enhance their retention by final products [43].

6.5Intelligent Packaging and pH Indicators

Anthocyanins have also found one of the most creative uses in smart food packaging. Anthocyanins are natural indicators that can be employed to measure the freshness and spoilage in food since they are pH sensitive and change their colour accordingly. As an illustration, it is possible to package films with anthocyanins that will transform their colour depending on the changes in pH due to the microbial activity in food products. It is especially applicable in perishable food product like meat and seafood, the change in pH is a sign of spoilage. Anthocyanin-based indicators can be used to improve food safety and allow consumers to receive real-time data regarding food quality [44].

6.6. Application in Edible Films and Coatings

The anthocyanins are also being used as an ingredient in edible films and coating to enhance the functional and aesthetic characteristics of food packaging. Such films serve not only as moisture and oxygen-protective screen layers but also as antioxidants and aesthetic qualities of food freshness. The incorporation of anthocyanins into biodegradable packaging products will be helpful in terms of sustainability, as it will help eliminate the use of synthetic packaging as well as encourage environmental-friendly options [45].

VII. CONCLUSION

The purple cabbage (Brassica oleracea var. capitata f. rubra) has potential to be a strong source of anthocyanins which can be used as natural pigments in the modern food systems because of their bright colour and health promoting qualities. They provide viable options to synthetic colorants, which is in line with the increasing need to have clean-label and sustainable food products. The review brings to the fore their structural features, sensitivity to environmental conditions as well as the benefit of purple cabbage as a plentiful and steady source of acylated anthocyanins. Different forms of extraction are used with the aim of increasing efficiency and sustainability, especially the green methods. But instability and variability in food systems are still a problem. Their stability and use can be improved by such strategies as encapsulation and process optimization. Altogether, purple cabbage anthocyanins could be defined as sustainable and multi-purpose ingredient, and the further improvements are required to facilitate their industrial application.

VIII. FUTURE SCOPE

The future of anthocyanin of purple cabbage in food system is bright and there is room to improve on extracting the product, stability, and use. More studies should be conducted to come up with effective green extraction processes and

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enhance stability using methods like encapsulation as well as using biopolymers based carriers. The anthocyanins also exhibit good prospects in smart packaging as natural pH sensors to monitor the freshness of foodstuffs. Nevertheless, there are still obstacles in terms of increasing production, lowering prices and standardisation of processes in terms of industrial use. The use of agricultural by-products can make the agricultural sector more sustainable and facilitate the idea of the circular economy. Also, their integration into the functional and customized nutrition must be further clinically tested. It will also need to address regulatory and safety concerns to expand commercialization and acceptance internationally.

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