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Anthocyanin-rich edible flowers, current understanding of a potential new trend in dietary patterns.

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A R T I C L E I N F O

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A B S T R A C T

Background: Among the many sources of anthocyanins, edible flowers are regaining interest for both consumers and researchers due to their nutritional profile and the need for even more healthy dietary alternatives. In such context, anthocyanin-rich edible flowers may be one of the most interesting groups of such cultivars but also of anthocyanins source.

Scope and approach: In this review, we discuss the latest findings regarding such type of edible flowers, from their consumption patterns to their nutritional and anthocyanins composition, their reported health benefits, the challenges about the consumption of edible flowers and the future research necessities on this promising thematic.

Key findings and conclusions: Anthocyanins have become a key group of natural compounds during the last years due to their broad applications in different areas. From a nutritional and health perspective, these compounds have been showing potential roles against different pathologies. The excellent aroma, taste and appearance of anthocyanin-rich edible flowers turns meals more appealing to consumers. Moreover, their nutritional profile, bioactive properties, and health benefits, encourages the development of functional foods with nutraceutical purposes, thus promoting the consumption of these type of edible flowers worldwide. Further knowledge in food processing methods is a key factor on the comeback and the addition of anthocyanin-rich edible flowers to our dietary habits.

1. Introduction

In light of the abundant health information available to them, consumers are increasingly seeking out healthier food alternatives to integrate into their dietary routines. Consequently, foodstuffs with a healthier nutritional profile have been gaining increased attention not only from the consumer but also from the food industry and scientific community (T. C. S. P. Pires, Barros, Santos-Buelga, & Ferreira, 2019). Preference is given to products derived from natural sources, namely, plant-based foods from organic farming, over their processed counterparts (Rupesh Mervin & Velmurugan, 2011; T. C. S. P. Pires et al., 2019; Rahman, Mele, Lee, & Islam, 2021).

Edible flowers have been conceived of as an innovative type of plant-based food. Sensorial properties such as aesthetic appeal and desirable aroma, nutraceutical profile such as phytochemicals and micronutrients, and consumers' desire for new flavors and gastronomic innovation (*e.g.* combination of flowers with other foods, including vegetables, meat, fish and some types of beer and wines) are relevant issues concerning the use of edible flowers (Benvenuti & Mazzoncini, 2021). A recently conducted review specifically highlighted the captivating sensorial and

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aromatic properties of edible flowers, emphasizing their appealing characteristics and positioning them as a significant emerging horticultural product (E. d. O. Pires et al., 2023). Moreover, their production satisfies the need for urban cropping and agriculture, as edible flowers crops can provide ready-to-eat food, locally produced with low transportation impact, and contribute to the increase of urban biodiversity especially in terms of pollinators (Eigenbrod & Gruda, 2015). In addition, the water footprint of flower cultivars is considerably lower than common crops such as wheat, rice, or beans. In this scenario, edible flowers are becoming more popular among both food manufacturers and nutritionists, representing an important segment to expand in the food market, with an estimated annual growth rate (CAGR) of 4.85% (2021–2026) and a cumulative growth of 31.17% (E. d. O. Pires et al., 2023).

The valorization of edible flowers has also been directed towards health and nutrition, especially following the growing scientific evidence of bioactive properties of some cultivars, mainly due to the presence of different classes of phytochemicals (Nowicka & Wojdyło, 2019). Anthocyanins, with their diverse range of structures, emerge as one of the most fascinating classes of compounds in this regard, playing a pivotal role as key chemical constituents responsible for the vibrant coloration observed in numerous edible flowers. In fact, such edible flowers rich in anthocyanins that range from deep red to blue and violet are among the most produced, consumed and processed types of edible flowers (Jadhav, Badwaik, Annapure, Casanova, & Alaskar, 2023). Their vibrant colors represent a key factor for their acceptance among consumers and professionals for different purposes including the direct consumption or their use and natural colorants.

Besides, anthocyanins are well related with health benefits in different contexts. Due to their antioxidant capacities, these compounds have been implied in a wide range of pathologies, including cancer, cardiovascular diseases, or metabolic diseases.

Therefore, anthocyanin-rich edible flowers represent one of the most interesting groups of such pigments' source, with a wide range of different species, with different types of anthocyanins, from simple to highly complex structures that may cover several health benefits (He et al., 2022).

The goal of this review is to demonstrate the potential of anthocyanins-rich edible flowers as part of a farm-to-fork strategy, allowing to produce sustainable, healthy, and appealing food products rich in bioactive compounds. From the consumption and composition of anthocyanins-rich edible flowers; preservation technologies; and nutraceutical properties, several topics are discussed herein.

2. Consumption and composition of edible flowers

2.1. Consumption of edible flowers

The use of flowers dates to 3000 BCE with flowers' cooking procedures emerging in ancient civilizations that used them as ingredients in different meals, salads, and drinks (Mlcek & Rop, 2011; L. Zhao et al., 2019). Edible flowers are reported as relish and flavor enhancers of many savories and sweet dishes in ancient Rome and Greece (L. Zhao et al., 2019). In today's gastronomy, edible flowers are commonly used with several foodstuffs, enhancing not only the visual appeal, but also adding a distinctive and new flavor to existing garnishes (Pinakin, Kumar, Suri, Sharma, & Kaushal, 2020). They can be incorporated into distinct dishes, ranging from desserts, salads, and soups to beverages such as tea and other types of infusions (Pinedo-Espinoza et al., 2020). In China, flowers of *Osmanthus fragrans Lour*, and *Flos Sophorae* have been used as raw materials to cook pastry, soup and congee (Cunningham, 2015). In some European countries, dandelion flowers (*Taraxacum officinale*) are added to drinks and salads directly for color, fragrance and flavor enhancement, while sugar boiled dandelion flowers and fried black elderberry flowers are used regularly (Rop, Mlcek, Jurikova, Neugebauerova, & Vabkova, 2012). Edible flowers are widely present in the Mediterranean diet and contribute to the well-known health-promoting properties of such food regime (Amrouche et al., 2022).

The acceptability of edible flowers by consumers depends on their sensorial qualities, which include their color, appearance, aroma, taste, and texture. A recent sensorial analysis performed in Iran with different species of Edible flowers revealed that the purple chrysanthemum species was the most attractive flower, mainly due to their deep purple color (Nicknezhad et al., 2023).

Other sensorial studies have identified some individual organoleptic characteristics (*e.g.* sweetness, spiciness, aroma, bitterness, consistency), as well as similarity with other vegetable and spices. For instance, *Tropaeolum majus* flowers were characterized by a spicy taste (like radish), while *Ageratum houstonianum* and *Begonia semperflorens* flowers presented carrot-like and lemon juice-like flavour, respectively (T. C. S. P. Pires et al., 2019).

In addition to these sensorial characteristics, personal attributes such as education, gender, annual income, or product presentation (composition of flowers, size, and price) also play a critical role in the selection of edible flowers (L. Fernandes, Casal, Pereira, Saraiva, & Ramalhosa, 2017; Rodrigues et al., 2017). In questionnaire survey performed in Portugal to a sample of 100 possible consumers aged between 20 and 84 years old, 77% of the inquires had consumed these products at least once, while 91% answered positively to if they heard about edible flowers before (R. P. F. Guiné, Santos, & Correia, 2017). A more recent study compared the habits, knowledge, and use of edible flowers between Portugal and Costa Rica. While in Portugal the most consumed edible flowers were rose, chamomile and wild pansies, in Costa Rica chamomile and pumpkin flowers seems to be the preferred (R. Guiné, Florença, Moya, & Anjos, 2020). Besides, in Portugal the main reasons for consumption were decoration and novelty, while in Costa Rica taste and decoration represented the main drivers of consumption (R. Guiné et al., 2020).

Regarding edible flowers consumption, the species that are rich in anthocyanins, share a fair amount on this matter worldwide with several types of blue, red and violet flowers being consumed in different contexts. For instance, within 32 species that are normally present in the Mediterranean diet, 16 are red, violet or blue flowers, rich in anthocyanins (Amrouche et al., 2022), and among the 5 most commonly consumed species in Iran, 3 are rich in these compounds (Nicknezhad et al., 2023). Common flowers, normally consumed in different contexts are presented in Table 1.

2.2. Nutritional and phytochemical composition of edible flowers

Typically, most authors divide edible flowers into three main parts: pollen, nectar, and petals. Pollen is rich in macronutrients such as proteins, lipids, and carbohydrates (T. C. S. P. Pires et al., 2019; Rivas-García et al., 2021). Nectar comprises not only a high quantity of free sugars but also some amino acids, proteins, and lipids in their composition. Petals constitute the major portion of the flower in terms of overall weight and are mainly composed of vitamins and minerals. Even though there is less research on stigmas as a part of edible flowers, there have been found, in some species, essential oils and carotenoids in their composition (Benvenuti & Mazzoncini, 2021).

Regarding specific composition, edible flowers are mainly composed of water, ranging from 70 to 95%, depending on the flower species (L. Fernandes et al., 2017; T. C. S. P. Pires et al., 2019). Carbohydrates are the most abundant macronutrients, predominantly glucose, fructose and sucrose (Rivas-García et al., 2021). Regarding fatty acids, edible flowers present a variable content (ranging from 0,1%–10% dry weight) (Luana Fernandes, Ramalhosa, Pereira, Saraiva, & Casal, 2018). In general, their fatty acid profile is close to that found in other vegetables such as lettuce and asparagus, and normally contain α-linolenic and linoleic acids (Rivas-García et al., 2021). Concerning protein content, edible flowers show a lower level when compared to animal-based foods (about 6 g/100 g, dry weight), but higher than what is found in some vegetables

Table 1
Anthocyanin-rich Edible Flowers normally consumed in daily diets.

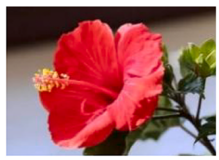
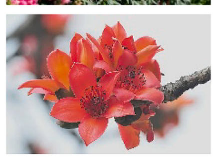
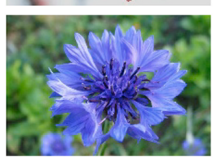
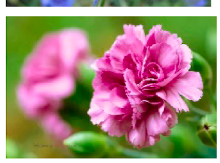
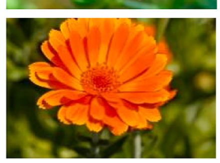
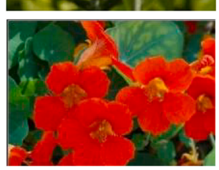
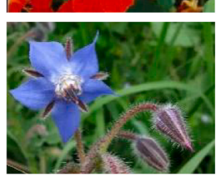
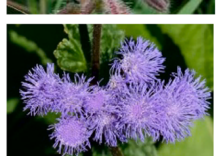
Scientific Name	Common name	Figure	Flavors	Edible use	References
Anchusa azurea P. Mill.	Garden anchusa and Italian bugloss		Slightly sweet and sour	Salad, tea, soup, boil, and fries	Loizzo et al. (2016)
Viola tricolor L.	Johnny Jump up and heartsease		Sweetish Vanilla taste	Salad, sauce, jelly, syrup, liquor, vinegar, honey, oil, candy, ice cube, tea, beverages, desserts	Koike et al. (2015)
Hibiscus sabdariffa L.	Roselle		Grassy taste	Flavoring agents, drink, jam, wine, ice cream, chocolates, puddings and cakes	Khan, Abdulbaqi, Darwis, Aminu, and Chan (2022)
Antirrhinum majus L.	Snapdragon		Slightly Bitter	Salad	Loizzo et al. (2016)
Bombax malabaricum L.	Cotton tree		Slightly bitter	Cooked and accompanied with meat and rice, tea, salad, decoction	Yasien et al. (2022)
Centaurea cyanus L.	Cornflower and bachelor's button		Bitter, sweet-to-spicy	Ingredient in tea and salad	(L. Fernandes, Pereira, Saraiva, Ramalhosa, & Casal, 2019)
Dianthus chinensis L.	Carnations		Sweet	Tea, cake, and decoction	Sreelekshmi and Siril (2023)
Calendula officinalis L.	Marigold or Scotch marigold		Slightly Bitter	Salad, omelets or as an accompaniment cheese	(Benvenuti et al., 2016; Kozlowska, Stachowiak, & Prus, 2019; Pedram Rad, Mokhtari, & Abbasi, 2019)
Tropaeolum majus L.	Garden nasturtium, Indian cress, and monks cress		Spicy	Salad, sauce, foodstuff and drink	Barrantes-Martínez et al. (2022)
Borago officinalis L.	Borage		Cucumber-like taste and slightly sweet	Cooked and accompanied with vegetable dishes, salad, soup, dessert	(Gilani, Bashir, & Khan, 2007; Kim, Hou, Lee, Kim, & Kim, 2010)
Ageratum houstonianum Mill.	Flossflower		Slightly bitter	Soup and decoction	Wiedenfeld and Andrade-Cetto (2001)

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Table 1 (*continued*)

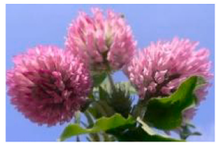
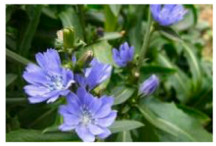
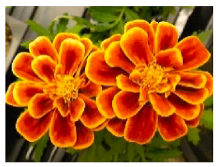
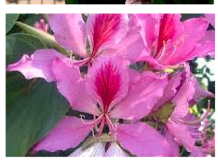
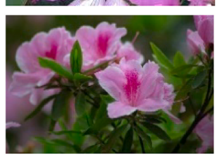
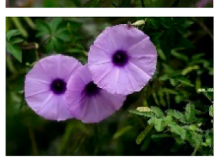
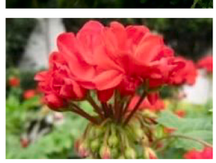
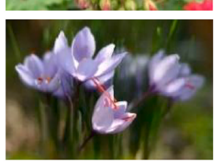
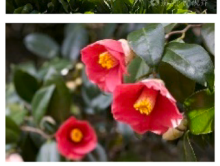
Scientific Name	Common name	Figure	Flavors	Edible use	References
Trifolium pratense	Red Clover		Sweet	Salad, soup, decoction	(Akbaribazm, Khazaei, & Khazaei, 2020; Kanadys, Baranska, Jedrych, Religioni, & Janiszewska, 2020)
Cichorium intybus L.	Chicory		Slightly bitter and sweet	Salad, soup and decoction	(Peña-Espinoza et al., 2022; Perović et al., 2021)
Tagetes erecta L.	French marigold		Spicy	Soup, cooked with flour, tea, decoction, cake, porridge	(Meurer et al., 2019; Zanovello et al., 2021; Ćetković, Djilas, Čanadanović-Brunet, & Tumbas, 2004)
Rosa damascena Mill	Rosa damascena, damask rose		Fragrant and sweet	Sauce, tea, cooked with meat, cake	(Erdogan Eliuz & Yabalak, 2022; Nikolova et al., 2016)
Bauhinia purpurea L.	Orchid Tree, Purple Butterfly Tree, Mountain Ebony, Geranium Tree, Purple Bauhinia		Slightly bitter	Cooked with eggs, salad, decoction	Lai, Lim, and Kim (2010)
Rhododendron spp.	Azalea		Sour	Tea, soup and porridge	Shootha, Tripathi, Singh, Kumar, and Ercisli (2022)
Ipomoea cairica (L.) Sweet	Messina creeper, Cairo morning glory, railroad creeper		Slightly bitter and sour	Soup, cooked with beef, decoction, porridge	Samuel, Lalrotluanga, Muthukumaran, Gurusubramanian, & Senthilkumar (2014)
Pelargonium × hortorum	Geranium		Rose and mint	Eat with honey, jam, ice cream, bake, and syrup	Nam and Choo (2021)
Crocus sativus L.	Saffron		Bitter, sweet, dry grass and shiitake	Tea and decoction	Moratalla-López, Sánchez, Lorenzo, López-Córcoles, and Alonso (2020)
Bellis perennis L.	Daisy		Slightly spicy and bitter	Decoction, salad, cake, fries, porridge	(Pehlivan Karakas, Sahin, Ucar Turker, & Verma, 2022)
Camellia japonica L.	Camellia		Wheat flavor	Salad, cooked with meat, fries, cake	Pereira et al. (2022)

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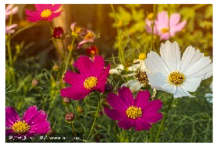
Table 1 (*continued*)

Scientific Name	Common name	Figure	Flavors	Edible use	References
Clitoria ternatea	Butterfly pea		Slightly spicy	Drink, tea, food colorants, cake	(Mukherjee, Kumar, Kumar, & Heinrich, 2008; Salacheep et al., 2020; Y. Wang et al., 2022)
Cosmos bipinnatus	Cosmos		Slightly bitter	Decoction, tea	(Botsaris, 2007; Jang, Park, Park, Park, & Lee, 2008)

like broccoli and cauliflower. There are some exceptions like sunflower and banana flowers, which present outstanding protein levels (Rivas-García et al., 2021; Takahashi, Rezende, Moura, Dominguete, & Sande, 2020). Phenylalanine, leucine and valine are the most abundant amino acids in some edible flowers, while threonine and lysine are the limiting amino acids (Sotelo, Lopez-Garcia, & Basurto-Pena, 2007). The fiber content of edible flowers is highly variable. Regarding micronutrients, minerals represent the most variable component in terms of content, with potassium, phosphorus, magnesium, and calcium being the main minerals that are found in edible flowers (L. Fernandes et al., 2017; Rivas-García et al., 2021). Regarding vitamins, riboflavin, vitamin A, C and niacin are some examples that are commonly found in edible flowers (Lara-Cortés, Osorio-Díaz, Jiménez-Aparicio, & Bautista-Baños, 2013; Rivas-García et al., 2021).

Edible flowers are also a very rich source of phytochemicals such as polyphenols, produced by plants to protect them from environmental damage and disease. They are also responsible for plant fragrance, taste, and pigmentation (Kumari, Ujala, & Bhargava, 2021; Pott, Osorio, & Vallarino, 2019; Rivas-García et al., 2021). In fact, polyphenols are the most abundant phytochemicals that can be found in edible flowers (Albuquerque, Heleno, Oliveira, Barros, & Ferreira, 2021), with flavonols such as kaempferol and quercetin derivatives the most common (Albuquerque et al., 2021; T. C. S. P. Pires et al., 2019). Catechin and epicatechin are the most common flavanols (Kumari et al., 2021; E. O. Pires, Jr., F. Di Gioia et al., 2021), while apigenin, luteolin, and chrysoeriol are common flavones that may also be found in edible flowers. Flavanones, such as naringenin, hesperidin, and hesperetin, can also be found in some of the edible flowers (E. O. Pires, Jr., F. Di Gioia et al., 2021). Regarding anthocyanins, the content is highly variable.

Another group of phytochemicals present in edible flowers are non-flavonoid compounds which include phenolic acids as the most abundant class (T. C. S. P. Pires et al., 2019; Tsao, 2010). Vanillic acid, gallic acid, and *p*-hydroxybenzoic acid are some examples of the most common hydroxybenzoic acids, whereas *p*-coumaric acid, ferulic acid, and caffeic acid are the most common hydroxycinnamic acids found in edible flowers (J. Chen, Yang, et al., 2020; E. O. Pires, Jr., F. Di Gioia et al., 2021).

Other phytochemicals such as carotenoids, chlorophylls, alkaloids, betalains, nitrogen-containing and organosulfur compounds can be also present (Lu, Li, & Yin, 2016; E. O. Pires, Jr., F. Di Gioia et al., 2021).

The variety of colors displayed by flower petals and fruits is a result of their co-evolution with fauna and as a response to external stress factors (Grotewold, 2006), with betalains, carotenoids, and anthocyanins as the main pigment classes. Betalains can be yellow, blue, and violet; carotenoids confer red and yellow tones; while anthocyanins can present blue, purple, and red hues (Benvenuti & Mazzoncini, 2021; Grotewold, 2006; E. O. Pires, Jr., F. Di Gioia et al., 2021). It is important to notice that the nutritional and phytochemical composition of edible flowers significantly varies with external factors such as regional soil composition and meteorological conditions. Flowers can also be harvested at different stages (before, during and after flowering) under varying conditions (i.e., wet, dry, or cool weather), which may affect the relative abundance of the different phytochemical compounds (E. O. Pires, Jr., F. Di Gioia et al., 2021).

3. Anthocyanins in edible flowers

3.1. Structural characterization

Anthocyanins represent one of the main classes of flavonoids present in the pink, red, purple, and blue edible flowers. These compounds contain the basic flavonoid structure normally represented as a typical C6–C3–C6 carbon chain (Fig. 1) (M. J. Lee, Park, Choi, & Jung, 2013), and due to the presence of sugar moieties, they are considered the major water soluble group of polyphenols, with more than 700 different structures described so far (Andersen & Jordheim, 2006; Santos-Buelga, Mateus, & De Freitas, 2014). Interestingly, only 6 anthocyanin aglycones give origin to all the different structures – delphinidin (Dp), cyanidin (Cy), petunidin (Pt), peonidin (Pn), pelargonidin (Pg) and malvidin (Mv) – that differ on their substitution pattern at ring B (Tsuda, 2012). The several hundreds of different derived structures are result of a complex network of substituents in different key atoms of the core skeleton. Hexoses and pentoses are the most common sugars moieties and are normally linked as mono-, di- or triglycosides to the aglycon structure. The attachment of the sugar to the C3 position is the most common due to the stabilization properties of this linkage to the overall structure of the anthocyanin. However, other glycosylation patterns may occur, namely at C5 and C7 positions, and less frequently and C3′ and C5’ (De Pascual-Teresa & Sanchez-Ballesta, 2008).

Monoglycosylated anthocyanins are the simplest structure. However, the majority of the anthocyanins described in flowers are

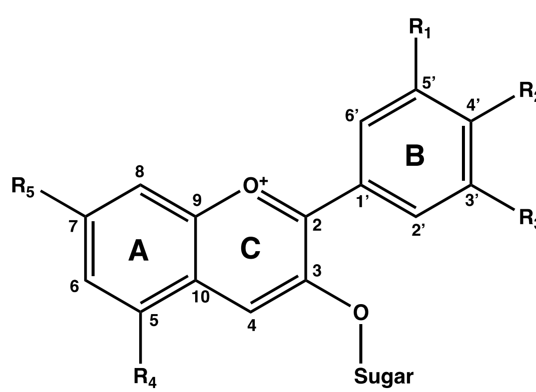


Fig. 1. Basic core skeleton of an anthocyanin on its flavylium cation form. A, B, and C represents the different rings on the structure of anthocyanins. R_1 – H, OH, OCH_3, Sugar; R_2 - H, OH, OCH_3; R_3 – H, OH, OCH_3, Sugar; R_4 – H, OH, Sugar; R_5 – H, OH, Sugar.

polyglycosylated anthocyanins, with either sequential sugars attached to the same position, or single/sequential sugars attached to different positions of the same core skeleton (He et al., 2022), making them a powerful source of such type of pigments (Fig. 2). This type of anthocyanins have been vastly reviewed in a previous work by He and colleagues, and are stated as one of the most promising type of anthocyanins for both health and technological usage (He et al., 2022).

Additionally, these sugars can be further acylated at the 6-OH (or less frequently at the 4-OH) position with different aromatic and aliphatic acids including *p*-hydroxybenzoic, *p*-coumaric, caffeic, ferulic, sinapic, malonic, acetic, or malic acids, originating acylated anthocyanins (Giusti & Wrolstad, 2003). A rare structure can also be found when more than one sugar moiety is present and the acyl group is connected to both, forming a cyclic structure, as in the case of the genus *Dianthus* (Okamura et al., 2013; Sasaki et al., 2013).

3.2. Colors and chemical stability

Anthocyanins specific color and intensity is extremely dependent on several factors, including pH, structural features (amount and position of methyl and hydroxyl groups, as well as different sugars and/or acids bound to their aromatic rings), complexation with metal ions or presence of other plant co-pigments (Alappat & Alappat, 2020; Benvenuti & Mazzoncini, 2021; Lysiak, 2022). Their stability is intimately related with their different colors and therefore depends on the same factors.

The most striking factor is pH, as anthocyanins naturally occur in an equilibrium network of different chemical species that depends on the pH values of their surroundings. At low pH values (<2), they are in their most stable form, the flavylium cation, which has a positively charged pyrylium ring (Fig. 1) and usually acquire an intense red color. As the pH increases, anthocyanins undergo two types of reactions that originate new structures. Proton-transfer reactions occur quickly, creating a quinoidal base. Water molecules can also attack the pyran ring, which happens at a slower rate, creating hemiketal forms that are more prevalent at slightly acidic pH ranges, resulting in a loss of color intensity. Other reactions also occur with the hemiketal structures, including tautomerization with the opening of the pyran ring, which result in the formation of chalcones (which contribute to the appearance of orange tones). At neutral pH, anthocyanins are mainly in the form of uncharged quinones and present a blue to violet color. At higher pH (usually higher than 7), anthocyanins start to lose their structural integrity and depending on their substitution patterns they can either be degraded immediately or originate anionic bases of each structure in equilibrium due to a deprotonation reaction (Pina, Oliveira, & de Freitas, 2015). Fig. 3 shows the different structures that anthocyanins may acquire depending on the pH values in solution.

Anthocyanins are also susceptible to other factors including temperature, light, oxygen, solvents, the presence of enzymes, other polyphenols, and metallic ions (Rein, 2005, pp. 10–14). Therefore, plants have developed different strategies to increase the stability of their secondary metabolites. For instance, co-pigmentation of anthocyanins with other compounds is the main mechanism that plant uses to stabilize their colors (He et al., 2022). Acylation of the sugar moieties with different aromatic and aliphatic units also seems to be a strategy that result in an overall increase resistance of anthocyanins to different degradation factors (C. L. Zhao et al., 2017).

3.3. Occurrence in edible flowers

Anthocyanins in edible flowers occur in a great number of structures mainly derived from the aglycones of cyanidin (T. C. S. P. Pires et al., 2019). Nevertheless, other aglycones derivatives are also present, including peonidin, petunidin, pelargonidin, delphinidin and malvidin.

Anthocyanins are important for the reproductive success of these

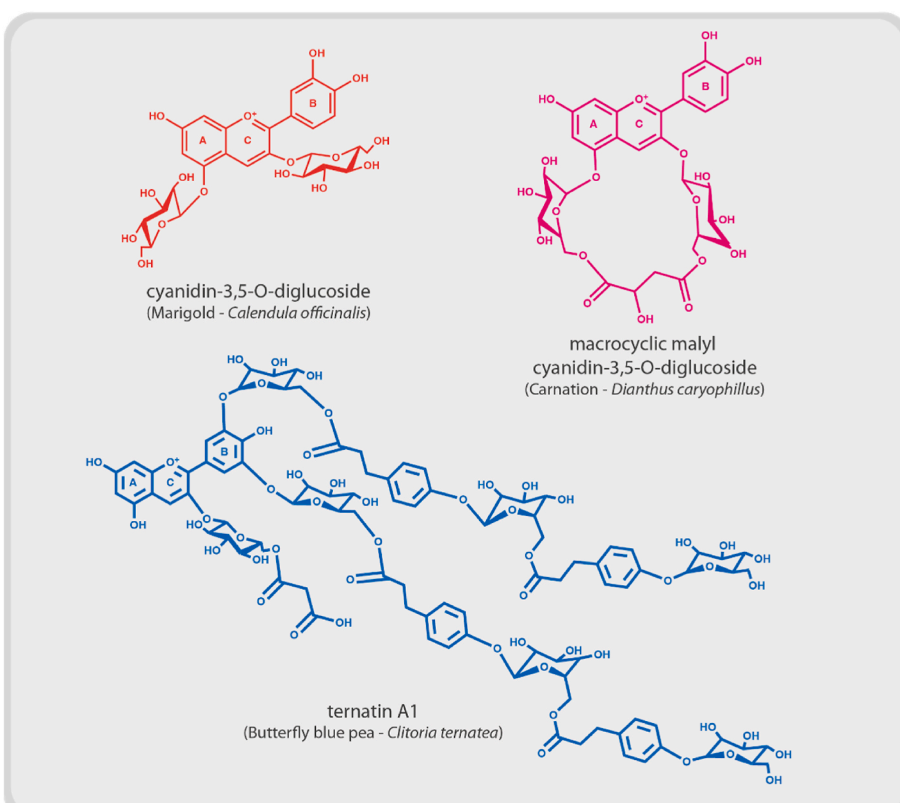


Fig. 2. Examples of polyglycosylated anthocyanins present in some typical Edible Flowers. The complexity can go from simple glycosylated sites to dense networks of intercalated sugars and acyl groups chains attached to different positions in the flavylium core structure.

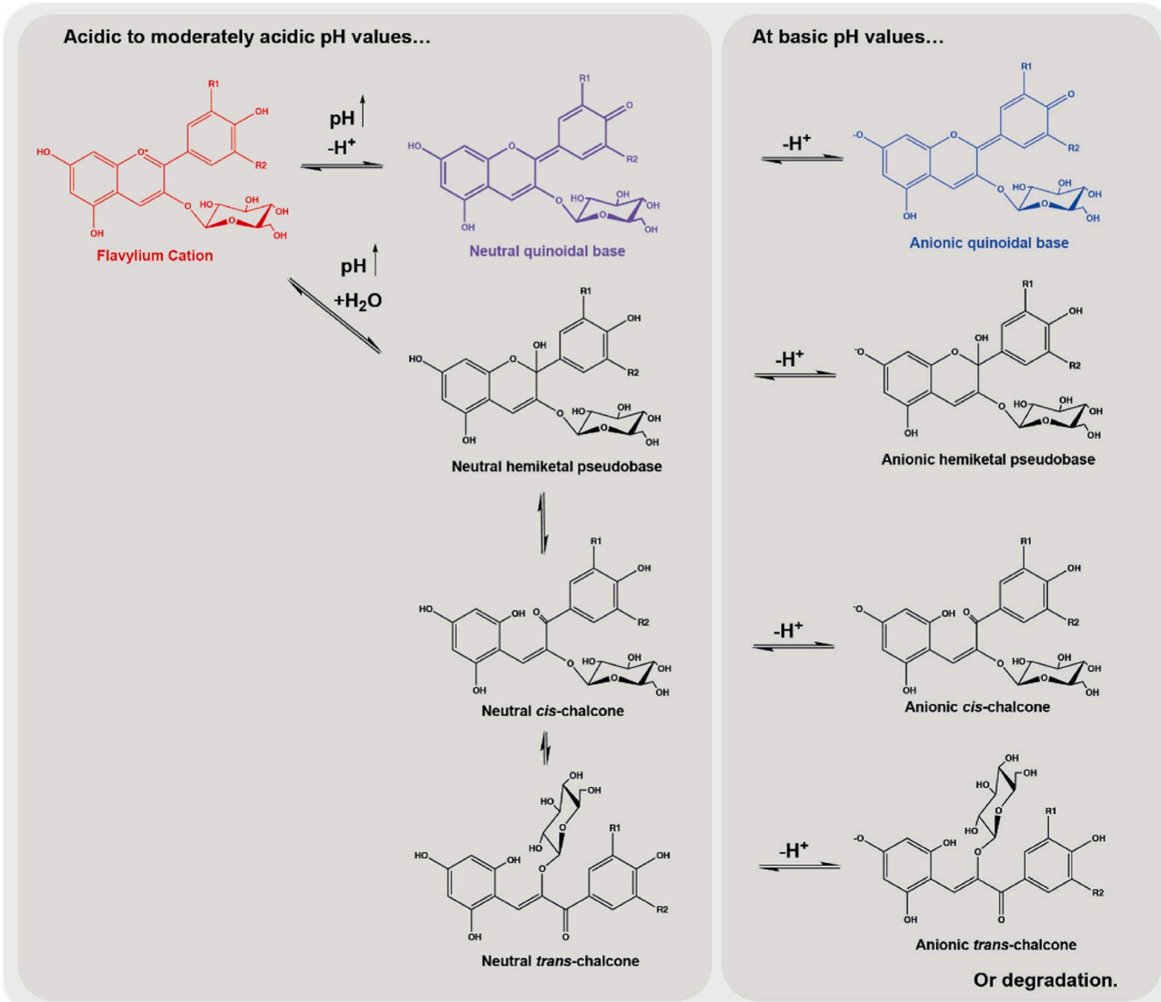


Fig. 3. Chemical equilibrium of anthocyanins in aqueous solution. R_1 and R_2 can be H, OH or OCH_3. The sugar attached (glucose) is merely representative of the most common glycosylation in anthocyanins at C3 position, other sugars can be attached at the same and other positions, as well as different acyl groups.

flowers and to their defense systems against aggressions such as microorganism infection or stress (Mannino, Gentile, Ertani, Serio, & Bertea, 2021; Rudall, 2020). Such facts, contribute to the vast number of different tones and patterns that anthocyanin-rich edible flowers acquire (Kumari et al., 2021; Kumari et al., 2022).

Peony, pansy, chrysanthemum, hibiscus, and rose are typical anthocyanins-rich edible flowers. Anthocyanins' complexity is highly variable within flowers species. For instance, purple bauhinia (*Bauhinia purpurea*) is mainly composed by cyanidin-3-*O*-glucoside (Li et al., 2014). Roselle flowers (*Hibiscus sabdariffa*), are rich in cyanidin-3-*O*-sambubioside (20.8 mg/g) and delphinidin-3-*O*-sambubioside (56.5 mg/g extract) (Alarcón-Alonso et al., 2012). On the other hand, carnation (*Dianthus caryophillus*) is rich in cyclic anthocyanins and butterfly pea (*Clitoria ternatea*) is rich in ternatins, a highly complex group of polyglycosylated anthocyanins (M. Nakayama et al., 2000; Vidana Gamage, Lim, & Choo, 2021). Adding to this, anthocyanins may differ between distinct subspecies of the same flower. For instance, peonidin-3,5-di-*O*-glucoside was reported in red "Caihi" peony as the main anthocyanin (D. Zhao, Tang, Hao, & Tao, 2015) and in the peony of "Gui Fei Cha Cui," pelargonidin-3,5-di-*O*-glucoside anthocyanin was identified (Fan, Zhu, Kang, Ma, & Tao, 2012). Also, the anthocyanin profile may vary depending on the developing stage of the flower (Barani, Zhang, Mujumdar, & Chang, 2022). Table 2 englobes a list of anthocyanin-rich edible flowers and their anthocyanin composition, while Tables S1 and S2, present their remaining phytochemical composition.

4. Health benefits of anthocyanin-rich edible flowers

The different health benefits of anthocyanin-rich edible flowers are often attributed to the presence of such pigments. These flowers have also been described to possess different bioactive behaviors in the context of different pathologies such as anti-diabetic, anti-aging, anti-oxidant, anti-inflammatory, anti-edematous, anti-HIV, immunomodulatory, cardioprotective, insecticidal, genotoxic, anti-tumor and other various biological activities *(Abdel-Haleem et al., 2017; Benvenuti, Bortolotti, & Maggini, 2016; L. Fernandes et al., 2017)*. Furthermore, this activity has also been found after digestive processes, thus highlighting the prolonged bioactive effect of the various phytochemicals (Chen et al., 2015).

Antioxidant. The most well recognized nutraceutical activity of anthocyanin-rich edible flowers is their antioxidant activity, which is related to their phytochemical composition. Flavonoids, mainly anthocyanins, flavonols and flavones play a critical role in the mitigation of the oxidative stress (Falla, Contu, Demasi, Caser, & Scariot, 2020; Mikołajczak, Sobiechowska, & Tańska, 2020) associated to the progression of several diseases. In relation to this, anthocyanins are particularly relevant, as edible flowers antioxidant activity can be positively correlated to the pigmentation intensity (brighter color), compared to cultivars of the same species with less pigmented flowers

Table 2
Anthocyanins content of anthocyanin-rich Edible Flowers.

Scientific name	Common name(s)	Anthocyanins	References
Bellis perennis	Daisy	Cyanidin 3-malonylglucoside Pelargonidin 3-malonylglucoside Delphinidin 3-O-glucoside	(N. Saito, Toki, Honda, & Kawase, 1988; Sawada et al., 2005)
Borago officinalis	Borage, Starflower	Delphinidin 3,5-O-diglucoside Petunidin 3,5-O-diglucoside	Salem et al. (2013)
Bauhinia purpurea	Purple bauhinia, butterfly tree, orchid tree	Cyanidin-3-O-glucoside	Li et al. (2014)
Begonia x tuberhybrida Voss.	Tuberous begonia, apple blossom	Malvidin 3,5-diglucoside Cyanidin 3-O-glucoside Pelargonidin 3-O-diglucoside Cyanidin 3-O-xylosylglucoside Cyanidin 3-O-rhamnosyldiglucoside	(Chirol & Jay, 1995; de Morais et al., 2020)
Calendula officinalis	Marigold	Cyanidin 3-O-glucoside Cyanidin 3,5-O-diglucoside Cyanidin 3-O-rutinoside Delphinidin-3-O-glucoside Malvidin-3-O-glucoside Peonidin-3-O-glucoside Pelargonidin-3,5-O-glucoside Petunidin-3-O-glucoside	Olennikov and Kashchenko (2013)
Camellia japonica	Camellia	Cyanidin 3-O-(6-O-(E)-p-coumaroyl)-β-glucopyranoside Cyanidin 3-O-(6-O-(E)-p-coumaroyl)-β-galactopyranoside Cyanidin 3-O-(6-O-(E)-caffeoyl)-β-glucopyranoside Cyanidin 3-O-(6-O-(E)-caffeoyl)-β-galactopyranoside	Pereira et al. (2022)
Campanula spp.	Bellflower	Pelargonidin 3-rutinoside-7-glucoside Cyanidin 3-glucoside Cyanidin 3-rutinoside	(Asen, Stewart, & Norris, 1979; Tanaka, Matsuura, Terahara, & Ishimaru, 1999)
Centaurea cyanus	Cornflower	Cyanidin-3,5-di-O-glucoside Cyanidin-3-O-(6″-malonylglucoside)-5-O-glucoside Cyanidin-3-O-glucoside Cyanidin-3-O-(6″-succinylglucoside)-5-O-glucoside	Lockowandt et al. (2019)
Chaenomeles spp.	Chinese quince	Cyanidin 3,5-O-Diglucoside Cyanidin-O-pentoside Cyanidin 3-rutinoside Cyanidin 3-O-glucoside Cyanidin O-syringic acid Peonidin 3-O-glucoside chloride	(T. Shen, Hu, Liu, Wang, & Li, 2020)
Cichorium intybus	Chicory, blue sailors	Delphinidin-3,5-di-O-(6-O-malonyl-β-D-glucoside) Delphinidin 3-O-(6-O-malonyl-β-D-glucoside)-5-O-β-D-glucoside Delphinidin 3-O-β-D-glucoside-5-O-(6-O-malonyl-β-D-glucoside) Delphinidin 3,5-di-O-β-D-glucoside	Nørbæk, Nielsen, and Kondo (2002)
Clitoria ternatea	Blue pea, butterfly pea flower	Delphinidin-3-O-β-glucoside Delphinidin-3-O-(2″-O-α-rhamnosyl)-β-glucoside Delphinidin-3-O-(2″-O-α-rhamnosyl-6″-O-malonyl)-β-glucoside Ternatins A1-A3, B1–B4, C1–C5 and D1-D3 Preternatins A3 and C4	(Kazuma, Noda, & Suzuki, 2003; Kogawa, Kazuma, Kato, Noda, & Suzuki, 2007; Terahara & Oda, 1996)
Cosmos bipinnatus	Cosmos	Cosmocyanin	(K. Saito, 1974, 1979)
Crocus sativus	Saffron	Delphinidin-3-O-glucoside Delphinidin-3,7-O-diglucoside Petunidin-3,7-O-diglucoside Petunidin-3-O-glucoside Malvidin-O-glucoside	Goupy, Vian, Chemat, and Caris-Veyrat (2013)
Dahlia mignon	Dahlia	Cyanidin-acetylhexoside Cyanidin-hexoside Pelargonidin-rutinoside Cyanidin-rutinoside Pelargonidin 3,5-di-O-glucoside Pelargonidin-hexoside	(Tânia C. S. P. Pires et al., 2018)
Dendranthema grandiflorum Ramat. (Chrysanthemum morifolium)	Garden chrysanthemum	Cyanidin 3-glucoside Cyanidin 3-(3"-malonyl)glucoside	(Park et al., 2015; N. Saito et al., 1988)
Dianthus caryophyllus	Carnation	3, 5-Di-O-(β-glucopyranosyl) pelargonidin 6″-O-4, 6″-O-l-cyclic malate 3, 5-Di-O-(β-glucopyranosyl) cyanidin 6″-O-4, 6″-O-l-cyclic malate Cyanidin 3-glucoside	(Li et al., 2014; M. Nakayama et al., 2000)
Glechoma hederacea	Ground-ivy, Creeping Charlie	Delphinidin 3-(6″-p-coumarylglucoside)-5-dimalonylglucoside Delphinidin 3-(6″-p-coumarylglucoside)-5-(6‴-malonylglucoside), as cis and trans	(N. Saito & Harborne, 1992)

(continued on next page)

Table 2 (*continued*)

Scientific name	Common name(s)	Anthocyanins	References
		Cyanidin 3-(6″-p-coumarylglucoside)-5-(4‴,6‴-dimalonylglucoside), as cis and trans Cyanidin 3-(6″-malonylglucoside)-5-glucoside	
Hemerocallis fulva	Daylily	Cyanidin-3-rutinoside (on H. fulva fm. Fulva and H. fulva fm. Rosea) Delphinidin-3-rutinoside (on H. fulva fm. Disticha)	Griesbach and Batdorf (1995)
Hibiscus rosa-sinensis	Chinese hibiscus	Cyanidin-3-sophoroside	Nakamura, Hidaka, Masaki, Seto, and Uozumi (1990)
Hibiscus sabdariffa	Roselle	Delphinidin-3-sambubioside Cyanidin-3-sambubioside	Du and Francis (1973)
Impatiens balsamina L.	Garden balsam, rose balsam	Pelargonidin-O-dihexoside Pelargonidin-O-hexoside-O-acetylhexoside Pelargonidin-O-hexoside-O-desoxyhexosyl-hexoside Malvidin-O-coumaroylhexoside-O-hexoside Malvidin-O-coumaroylhexoside Malvidin-O-acetylhexoside-O-coumaroylhexoside Peonidin-O-acetylhexoside-O-p-coumaroylhexoside	Pires, Pereira, et al. (2021)
Impatiens walleriana	Busy Lizzie	Peonidin-O-acetylhexoside-O-p-coumaroylhexoside Pelargonidin-O-p-coumaroyl-hexoside-O-acetyl-hexoside Pelargonidin-O-hexoside-O-desoxyhexoside-hexoside Malvidin-O-acetylhexoside-O-p-coumaroylhexoside Malvidin-3-O-p-coumaroylhexoside-O-hexoside	(E. d. O. Pires et al., 2021)
Ipomoea cairica	Messina creeper, Cairo morning glory, railroad creeper	Cyanidin 3-O-5-O-β-D-glucopyranoside Cyanidin 3-O-[2-O-(6-O-(E)-p-coumaroyl-β-d-glucopyranosyl)-6-O-(E)-caffeoyl-β-d-glucopyranoside]-5-O-β-D-glucopyranoside Cyanidin-3-O-[2-O-(2-O-(E)-p-coumaroyl-β-d-glucopyranosyl)-6-O-(E)-caffeoyl-β-d-glucopyranoside]-5-O-β-D-glucopyranoside Cyanidin 3-O-[2-O-(6-O-(E)-caffeoyl-β-d-glucopyranosyl)-6-O-(E)-caffeoyl-β-d-glucopyranoside]-5-O-β-D-glucopyranoside Cyanidin 3-O-[2-O-(2-O-(E)-caffeoyl-β-d-glucopyranosyl)-6-O-(E)-caffeoyl-β-d-glucopyranoside]-5-O-β-D-glucopyranoside Cyanidin 3-O-[(2-O-β-d-glucopyranosyl)-6-O-(E)-caffeoyl-β-d-glucopyranoside]-5-O-β-d-glucopyranoside	Pomilio and Mercader (2017)
Lavandula angustifolia Mill.	Lavender	Cyanidin, pelargonidin and malvidin glycosides	Costea, Străinu, and Gîrd (2019)
Lonicera japonica Thunb.	Japanese honeysuckle	Cyanidin-3-diglucoside-5-glucoside Cyanidin-3-rutinoside-5-glucoside Cyanidin-3,5-diglucoside Cyanidin-3-(p-coumaroyl)-rutinoside-5-glucoside Cyanidin-3-rutinoside Cyanidin-3-galactoside Cyanidin-3-glucoside Cyanidin-3-(acetyl)-glucoside	Yuan, Yang, Yu, Huang, and Lin (2014)
Magnolia spp.	Magnolia	Cyanidin-glucosyl-rhamnosyl-glucoside Peonidin-glucosyl-rhamnosyl-glucoside Cyanidin-glucosyl-rhamnoside Peonidin-glucosyl-rhamnoside	(N. Wang et al., 2019)
Malus spp.	Apple flower	Cyanidin-3-O-galactoside Cyanidin-3,5-O-diglucoside Cyanidin-3-O-rutinoside Cyanidin-3-O-arabinoside	Han, Zhao, Meng, Yin, and Li (2023)
Monarda didyma	Bergamot, scarlet beebalm	Monardaein: Pelargondin-3-O-(6-O-trans-p-coumaryl-β-d-glucopyranosyl)-5-O- (4,6-di-O-malonyl-β-d-glucopyranose	Kondo, Nakane, Tamura, and Goto (1985)
Monarda fistulosa	Wild bergamot, beebalm	Pelargonidin 3,5-diglucoside acylated with coumaric and malonic acids	Davies (1992)
Musa spp.	Banana blossom	Delphinidin-3-rutinoside Cyanidin-3-rutinoside Petunidin-3-rutinoside Pelargonidin-3-rutinoside Peonidin-3-rutinoside Malvidin-3-rutinoside	Kitdamrongsont et al. (2008)
Ocimum basilicum	Purple Basil (flower)	Cyanidin-3-glucoside-5-(6-malonyl)-glucoside Cyanidin malonyl-glucoside Cyanidin-3-(6,6′-di-p-coumaroyl)sophoroside-5-glucoside Cyanidin-3-(6-p-coumaroyl-malonyl-6′-p-coumaroyl) sophoroside-5-glucoside	Prinsi, Morgutti, Negrini, Faoro, and Espen (2019)
Paeonia officinalis L.	Peony	Peonidin 3,5-di-O-glucoside Cyanidin 3,5-di-O-glucoside	Jia et al. (2008)
Passiflora incarnata	Passion flower	Cyanidin 3,5-O-diglucoside Petunidin 3,5-O-diglucoside	Aizza, Sawaya, and Dornelas (2019)

(*continued on next page*)

Table 2 (*continued*)

Scientific name	Common name(s)	Anthocyanins	References
		Peonidin 3,5-O-diglucoside	
		Malvidin 3,5-O-diglucoside	
Pelargonium spp.	Geranium	Malvidin 3-O-glucoside-5-O-[6-acetylglucoside]	Mitchell, Markham, and Boase (1998)
		Malvidin 3,5-di-O-glucoside	
		Delphinidin 3,5-di-O-glucoside	
		Petunidin 3,5-di-O-glucoside	
		Peonidin 3,5-di-O-glucoside	
		Delphinidin 3-O-glucoside-5-O-[6-acetylglucoside]	
		Petunidin 3-O-glucoside-5-O-[6-acetylglucoside]	
Petunia hybrida	Petunia	Peonidin-3-p-coumaroyl-5-glucoside	Griesbach, Asen, and Leonnarat (1991)
		Peonidin-3-caffeoylrutinoside-5-glucoside	
		Malvidin-3-caffeoylrutinoside-5-glucoside	
		Cyanidin-3-glucoside	
		Cyanidin-3-rutinoside	
Phalaenopsis	Moth Orchid	(3′,7-di-O-sinapoyl-glucosyl)-3-glucosyl-cyanidin	Lam et al. (2019)
Platycodon grandiflorus	Balloon flower, chinese bellflower	Delphinidin-3-rutinoside-7-glucoside Platyconin: (delphinidin-3-di-caffeoylrutinoside-5-glucoside)	Ji et al. (2020)
Rosa spp.	Rose	Cyanidin 3,5-diglucoside Delphinidin 3,5-diglucoside	Wan et al. (2019)
Syringa vulgaris L.	Lilac	Rutinosides or coumaroyl hexosides of delphinidin and cyanidin	Deeva et al. (2022)
Tagetes patula	French marigold	Cyanidin-3-galloylsophoroside Cyanidin-3-glucoside Cyanidin-3-sophoroside	Deineka, Kulchenko, Blinova, Deineka, and Chulkov (2016)
Thymus spp.	Thyme	Cyanidin 3-(6″-malonylglucoside)-5-(6‴-malonylglucoside) Cyanidin 3-(6″-malonylglucoside) Cyanidin 3-(6″-malonyl-acetylglucoside) Peonidin 3-(6″-malonylglucoside)-5-(6‴-malonylglucoside) Pelargonidin 3-(6″-malonyl-acetylglucoside)	Diaz-Garcia et al. (2015)
Torenia spp.	Wishbone flowers, bluewings	Malvidin-3-O-β-D-glucoside Peonidin-3-glucoside-5-(p-coumaroyl)-glucoside	Fukusaki et al. (2004)
Trifolium pratense	Red clover	Malvidin-3-O-galactoside Peonidin-3-O-galactoside Cyanidin-3-O-galactoside Petunidin-3-O-galactoside Delphinidin-3,5-O-diglucoside Petunidin-3-O-rutinoside Cyanidin-3-O-glucoside	(S. G. Lee, Brownmiller, Lee, & Kang, 2020)
Tropaeolum majus	Garden nasturtium, Indian cress, monks cress	Pelargonidin-3-O-sophoroside Delphinidin-3-O-3-dihexoside Cyanidin-3-O-sophoroside	Garzon, Manns, Riedl, Schwartz, and Padilla-Zakour (2015)
Tulipa spp.	Tulip	Cyanidin 3-rutinoside Cyanidin 3-(2‴-acetylrutinoside) Delphinidin 3-rutinoside Delphinidin 3-(2‴-acetylrutinoside) Delphinidin 3-(3‴-acetylrutinoside) Pelargonidin 3-rutinoside Pelargonidin 3-(2‴-acetylrutinoside)	(Masayoshi Nakayama et al., 2004)
Viola odorata	Common violet, sweet violet	Delphinidin-3-(4’’-p-coumaroyl)-rutinoside-5-glucoside (violanin)	Singh, Dhariwal, and Navneet (2018)
Viola tricolor	Wild pansy, heartsease	Delphinidin-3-(4″-p-coumaroyl)-rutinoside-5-glucoside (violanin) Cyanidin-3-(coumaroyl)-methylpentosyl-hexosyl-5-hexoside Cyanidin-3-O-rutinoside Delphinidin-3-O-rutinoside	Koike et al. (2015)
Viola × wittrockiana	Pansy	Delphinidin-3-(4’’-p-coumaroyl)-rutinoside-5-glucoside (violanin) Petunidin-3-(4’’-p-coumaroyl)-rutinoside-5-glucoside Cyanidin-3-(4’’-p-coumaroyl)-rutinoside-5-glucoside Malvidin-3-(4’’-p-coumaroyl)-rutinoside-5-glucoside	Skowyra, Calvo, Gallego, Azman, and Almajano (2014)

(Benvenuti et al., 2016; Khoo, Azlan, Tang, & Lim, 2017) as well as other compounds, such as vitamins and essential oils (Benvenuti et al., 2016). Anthocyanins (*i.e.* delphinidin derivative, cyanidin derivative, pelargonidin 3-sophoroside) and phenolics present in *Tropaeolum majus* play an important role as antioxidants due to ABTS and DPPH radicals scavenging activities (458 and 91.87 μM Trolox equivalent/g FW, respectively) (Garzón & Wrolstad, 2009). Compared with other non-anthocyanin-rich edible flowers, extracts of *Rosa rugosa*, *Limonium sinuatum*, *Pelargonium hortorum*, *Jatropha integerrima* and *Osmanthus fragrans* were found to have the highest FRAP and Trolox equivalent antioxidant capacity (TEAC) (Li et al., 2014). Another study found that Ashwini, a dark colored variety of Rosa hybrida L. possessed antioxidant activity of 512.71 μmol Trolox equivalent/g which was positively correlated with its anthocyanin content (Kumari et al., 2017).

Cancer. Such as in the case of antioxidant properties, anthocyanin-rich edible flowers have also been described as having an active role against the development on different types of cancer, in both *in vitro* and *in vivo* animal studies. Dahlia flowers and roses extract, respectively, inhibited the growth of tumor cells of cervical and hepatocellular carcinoma cells. The hydroethanolic extract from *B. variegata* flowers also showed cytotoxic action against cervical carcinoma cells (Villavicencio et al., 2018). *In vitro* studies showed that aqueous Rose and Pea flowers extracts had potent cytotoxic and apoptotic effect on lymphatic cells (DAUDI cells) (Fakhri et al., 2021). As a rich source of flavonoids, *Hibiscus sabdariffa* was shown to be cytotoxic to T47D breast cancer cells (Kaulika & Febriansah, 2019). *Viola tricolor* extracts induced the apoptosis in different cancer cell lines from breast (MCF-7 human breast cancer cells) and from brain (Neuro2a mouse neuroblastoma cells) (Sadeghnia et al., 2014). However, the authors attributed these properties, mainly to the non-aqueous fractions that did not contained anthocyanins. On the other hand, the hydroalcoholic extract of *Viola odorata*, rich in anthocyanins, was able to decrease the tumorigenic activity of human glioblastoma GBM cells in a dose and time-dependent manner. The authors also confirmed that the mechanism of action involved the activation of the mitochondrial death pathway and caspase-3 (Hashemi et al., 2019). The ethanolic extract of the species *Dianthus chinensis* showed to induce the apoptosis of HepG2 hepatocellular carcinoma cells, which involved the induction of chromatin condensation, activation of caspases and cleavage of poly (ADP-ribose) polymerase protein (Nho, Chun, & Kim, 2012). *Clitoria ternatea* anthocyanin derivatives showed to have a much higher antiproliferative effect on Hep-2 carcinoma cells than the other compounds present in this species (Y. Shen et al., 2016).

Cardiovascular diseases. Cardiovascular diseases (CVDs) are the most prevalent causes of death, accounting for approximately 30% of deaths worldwide. Medicinal herbs, owing to their known beneficial properties and lower side-effects, have been used as alternatives to conventional therapies for the treatment of many diseases, including CVDs (Shaito et al., 2020). As mentioned above, the phytochemical composition of edible flowers is mainly responsible for their bioactivities, as one of the many flavonoid mechanisms of action is preventing the oxidation of the low-density lipoprotein and consequently stimulating vasodilatation (Bachheti et al., 2022). The cardioprotective effect of a *Viola tricolor* L. crude extract in a rabbit animal model of acute myocardial infarction and left ventricular hypertrophy was investigated (Saqib et al., 2020). The application of the extract on isolated rabbit atrial vein exhibited both negative chronotropic and inotropic effects (such as verapamil), and on the isolated aorta it exhibited a vasorelaxant activity. Through additional *in vivo* assays, *Viola tricolor* L. extract was shown to promote hypotensive and cardioprotective effects. Furthermore, it were shown the effects of *Trifolium pratense* flavonoid extract on isoproterenol-induced myocardial injury in rats (M. Wang et al., 2014). The extract exerted positive effects, including inhibition of oxidative stress and apoptosis of cardiac myocytes, along with the modulation of MAPK pathways.

Neuroprotective effects. A hydrogen peroxide-induced SH-SY5Y cell model was used to study the neuroprotective effect of an ethanolic extract of *Hibiscus sabdariffa* (Shalgum et al., 2019). The results revealed that the *H. sabdariffa* extract (at 100 μg) exhibited the best neuroprotection due to its antioxidant action, blocking mitochondrial dysfunction and apoptosis induced by hydrogen peroxide. A broader study reported that *Viola* x *wittrockiana* have a better neuroprotective activity *in vitro* than *Viola cornuta* by inhibiting the activities of acetylcholinesterase and monoamine oxidase A, and the results were associated with its higher content in bioactive compounds (emphasizing petunidin-3-*O*-rutinoside) (Moliner et al., 2019).

Metabolic effects. *Malva sylvestris* ethanolic extract inhibited both α-amylase and α-glucosidase activity in a concentration-dependent manner, and IC_{50} values were 7.8 and 11.3 μg/mL, respectively. The hypoglycemic effects may be due to the combined action of anthocyanins (0.3 ± 0.1 mg/g extract), carotenoids (1.3 ± 0.1 mg/g extract), flavonoids (12.7 ± 0.1 mg of quercetin equivalents/g extract, *i.e.* kaempferol, myricetin, luteolin, quercetin, rutin) and other phenolics (Loizzo et al., 2016).

Another study showed that an ethanolic extract of *Bauhinia variegata* flower possessed significant antidiabetic, anti-hyperlipidemic activities in streptozotocin (STZ) induced diabetic rats due to the presence of polyphenols (Tripathi, Gupta, & Singh, 2019). The extract normalized the damaged tissues and inflammation of kidney, liver and pancreas, reduced blood glucose level, cholesterol, triglyceride, low-density lipoprotein (LDL), very low-density lipoprotein (VLDL), free radicals' level and increases high density lipoprotein (HDL) level. This was associated with the presence of flavonoids (*e.g.* trifolin, nicotiflorin) and anthocyanins (*e.g.* cynidin-3-glucoside, malvidin-3-diglucoside, peonidin-3-glucoside and peonidin-3-diglucoside). A different study reported that *Punica granatum* flower polyphenols extract enhanced both liver and muscle glycogen and insulin signaling activities in type 2 diabetic rats (Tang et al., 2018). Furthermore, another study demonstrated that a polyphenol-rich extract from *Rosa rugosa* Thunb. activated phosphatidylinositol 3-kinase (PI3K)/protein kinase B (AKT) signaling pathway and showed greater antioxidant activity along with insulin sensitivity improvement and glucose tolerance on diabetic rats (Liu, Tang, Zhao, Xin, & Aisa, 2017).

Studies revealed that *Hibiscus sabdariffa* derived bioactive compounds (*e.g.* organic acids, anthocyanins, flavonoids, phenolic acid) are effective in the decline of body weight, regulation of cholesterol metabolism, suppression of adipogenesis and inhibition of lipid accumulation (Ojulari, Lee, & Nam, 2019). Aqueous extract of butterfly pea petals that has mainly flavonoids (anthocyanins) was found to have anti-obesity activity as it inhibited high-fat, high-fructose diet-induced body weight gain, alleviated insulin resistance, relieved hepatic oxidative stress, suppressed inflammation, lowered LDL-C levels and activated the PPARγ-LXRα-ABC pathway (Y. Wang et al., 2022). Also, this species showed an antidiabetic effect on diabetic mice through the modulation of the antioxidant and anti-inflammatory environments (Widowati et al., 2023).

Anti-aging. Several studies have been conducted regarding the anti-aging effects of edible flowers extracts, which have been shown to prevent or even improve skin aging (*e.g. Camellia japonica* L., *Clitoria ternatea* L. and *Rosa damascena* Mill.), neurodegeneration (*e.g. Hibiscus sabdariffa* L. and *Chrysanthemum morifolium* Ramat.), immunosenescence (*e.g. Camellia sinensis* L.) and lifespan (*e.g. Hibiscus sabdariffa* L., *Lonicera japonica* Thunb. and *Rosa rugosa* Thunb.) (Q. Chen, Yang, et al., 2020). It is important to mention that studies regarding the anti-aging effects associated with the consumption of edible flowers have all been performed in cells or appropriate animal models.

Microbicidal activity. A study showed the effects of a *Centaurea cyanus* extract against several Gram-negative and Gram-positive bacteria. The extract was effective against all the microorganisms tested; however, it was more active against Gram-positive bacteria, particularly *Staphylococcus aureus* and *Listeria monocytogenes*, both with a minimum inhibitory concentration (MIC) of 2,5 mg/mL (Lockowandt et al., 2019). Furthermore, another study demonstrated the effects of a hydroethanolic extract of *Hibiscus sabdariffa* against bacterial and fungal strains. The extract exhibited both antibacterial and antifungal properties against all strains, with MIC values ranging from 0,15 to 0,2 mg/mL for all bacterial strains, whereas the lowest MIC for fungi (0,075 mg/mL) was obtained for *Trichoderma viride*, indicating a stronger antifungal activity of the extract against this strain (Jabeur et al., 2017).

Table 3 describes some common anthocyanin-rich edible flowers and their medicinal uses.

5. Challenges in edible flowers consumption

5.1. Toxicity, anti-nutritional substances, and other contaminants

Not all flowers can be eaten, and some might even be toxic. To be considered edible, a flower must not only be free from both chemical and biological hazards, but also possess a good nutritional composition that makes it worthy of being introduced into a daily diet (Navarro-Gonzalez, Gonzalez-Barrio, Garcia-Valverde, Bautista-Ortin, & Periago, 2014). Globally, there is a wide variety of edible flowers species, and only a small portion has been thoroughly investigated and submitted for toxicological studies (T. C. S. P. Pires et al., 2019). Visually, flowers intended for ornamental purposes share a similar appearance to those that have already been identified as edible. This represents

Table 3
Reported bioactive properties of anthocyanin-rich Edible Flowers.

Scientific Name	Common name	Bioactive properties	References
Anchusa azurea P. Mill.	Garden anchusa and Italian bugloss	Depurative, antitussive, diaphoretic, and diuretic	Loizzo et al. (2016)
Viola tricolor L.	Johnny Jump up and heartsease	Prevention of various cancers; antiallergenic, antiatherogenic, anti-inflammatory, antimicrobial, antioxidative, antithrombotic, cardioprotective and vasodilator activities	Koike et al. (2015)
Hibiscus sabdariffa L.	Roselle	Cardioprotective, antilipidemic, antihypertensive, hepatoprotective, antidiabetic immunomodulatory, and antioxidant effects; treatment of chronic diseases like high blood pressure, liver diseases, fever, inflammation, mutagenicity	Khan et al. (2022)
Bombax malabaricum L.	Cotton tree	Hypoglycaemic, treatment of skin diseases, haematuria, cancer, snake bites, sores, boils, anaemia, premature ejaculation, menstrual disorders, hydrocoele, permanent sterilization, gonorrhoea and colitis and as a laxative, diuretic and astringent	Yasien et al. (2022)
Centaurea cyanus L.	Cornflower and bachelor's button	Anti-inflammatory, skin cleansing, assisting regulating digestion and kidney, gall bladder, liver, and menstrual disorders, and increasing immunity	(L. Fernandes et al., 2019)
Dianthus chinensis L.	Carnations	Treatment of urinary infection, carcinoma, viral infection, carbuncles, gonorrhea, and neuro-related problems; anti-microbial, diuretic anti-inflammatory, anticancer, and cholesterol-lowering effects	Sreelekshmi and Siril (2023)
Calendula officinalis L.	Marigold or Scotch marigold	Antioxidant, antiseptic, free radicals' inhibitors, anticancer, antibacterial, antifungal, antiviral, anti-inflammatory activities and cure skin wounds	(Benvenuti et al., 2016; Kozlowska et al., 2019; Pedram Rad et al., 2019)
Tropaeolum majus L.	Garden nasturtium, Indian cress, and monks' cress	Antimicrobial, antiviral, anti-inflammatory and antioxidative effects	Barrantes-Martínez et al. (2022)
Borago officinalis L.	Borage	Modulate obesity, asthma, bronchitis, cramps, diarrhea, palpitations, kidney, multiple sclerosis, and premenstrual ailments; anti-inflammatory, anti-fibrotic, antioxidant and anti-proliferative effects; improve skin barrier and against skin photodamage	(Gilani et al., 2007; Kim et al., 2010)
Ageratum houstonianum Mill.	Flossflower	Against pain and infections, clean external wounds.	Wiedenfeld and Andrade-Cetto (2001)
Trifolium pratense	Red Clover	Reduce blood glucose, lipids, pressure; treat cardiovascular disease; anti-tumor effect, increase immune system and treat Alzheimer's disease	(Akbaribazm et al., 2020; Kanadys et al., 2020)
Cichorium intybus L.	Chicory	Anti-inflammatory, anti-parasitic, hepatoprotective, antioxidative, sedative, immunological, cardiovascular, hypolipidemic, antidiabetic, anticancer, gastro-protective, antimicrobial effects	(Peña-Espinoza et al., 2022; Perović et al., 2021)
Tagetes erecta L.	French marigold	Therapeutic usage in skin complaints, wounds, burns, conjunctivitis, poor eyesight, menstrual irregularities, varicose veins, hemorrhoids, duodenal ulcers, cardiovascular, renal, and gastrointestinal diseases, including stomatitis, dyspepsia, and diarrhea; diuretic effect	(Meurer et al., 2019; Zanovello et al., 2021; Ćetković et al., 2004)
Rosa damascena Mill	Damask rose	Scavenging free radicals, anticancer, anti-inflammatory, antimutagenic, anti-HIV, antidepressant, laxative, prokinetic, anti-aging, anti-diabetic, antimicrobial, analgesic effects, treatment of abdominal pain, chest pain, menstrual bleeding, digestive problems, headaches, and migraines	(Erdogan Eliuz & Yabalak, 2022; Nikolova et al., 2016)
Bauhinia purpurea L.	Orchid Tree, Purple Butterfly Tree, Mountain Ebony, Geranium Tree, Purple Bauhinia	Nephroprotective, thyroid hormone regulating, antibacterial, antidiabetic, analgesic, anti-inflammatory, anti-diarrheal, antibacterial, antioxidative and antitumor activities	Lai et al. (2010)
Rhododendron spp.	Azalea	Anti-inflammatory, anti-analgesic, antimicrobial, antiviral, antioxidative, anti-diabetic, anticancer, hepatoprotective and cardioprotective effects	Shootha et al. (2022)
Ipomoea cairica (L.) Sweet	Messina creeper, Cairo morning glory, railroad creeper	Antimicrobial, spasmolytic, anti-rheumatic, anti-inflammatory, anti-HIV, antipyretic, anti-tumor anti-cancer, analgesic, spasmogenic, hypotensive, psychotomimetic activities; treatment of tuberculosis, cough, asthma, acute and chronic viral hepatitis type B, liver cirrhosis and jaundice	Samuel, LalrotluangaMuthukumaran, Gurusubramanian, and Senthilkumar (2014)
Pelargonium × hortorum	Geranium	Pharmacological effects of itching, bruising, shigellosis, enteritis, chronic diarrhea, and liver disorders	Nam and Choo (2021)
Crocus sativus L.	Saffron	Antioxidative, anti-carcinogenic, memory enhancer, and neuroprotective effects; improve anxiety and depression induced by UCMS	Moratalla-López et al. (2020)
Bellis perennis L.	Daisy	Wound healing, anxiolytic, antitumor, antibacterial, antifungal, anti-hyperlipidemic, antioxidative, postpartum anti-hemorrhagic therapeutic impacts and pancreatic lipase inhibitor	(Pehlivan Karakas et al., 2022)
Camellia japonica L.	Camellia	Gastrointestinal modulators, anticancer, antimicrobial, antioxidant, neuroprotective, hypolipidemic, anti-obesity, and anti-inflammatory agents	Pereira et al. (2022)
Clitoria ternatea	Butterfly pea	Antioxidative, antimicrobial, antihypertensive, anti-inflammatory, antibacterial, antidiabetic, anti-hypertensive effects and cancer cell reduction action; treatment of stress and depression; inhibiting oxidation of human low-density lipoprotein, cholesterol, DNA strand scission, hypertension, and kidney damage	(Mukherjee et al., 2008; Salacheep et al., 2020; Y. Wang et al., 2022)
Cosmos bipinnatus	Cosmos	Treatment of jaundice, intermittent fever, splenomegaly; anti-inflammatory, antioxidative and antigenotoxic activities	(Botsaris, 2007; Jang et al., 2008)

a problem because the ornamental flower cultivation process, involving the use of several chemical treatments, differs from that used for edible flowers, which consists of a controlled, organic-based process (T. C. S. P. Pires et al., 2019; Rop et al., 2012). To avoid risks to consumer's health such as food poisoning or, in a more extreme case, death, identification of the flowers that can be used for edible purposes is essential (L. Fernandes et al., 2017; Takahashi et al., 2020). Another key factor to consider is that edible species look like wild species, that is, those that grow spontaneously in nature and might contain toxic compounds and/or be contaminated. Considering this, it is important to know the flowers' place of origin to be able to discriminate them (Takahashi et al., 2020). To date, there are still no available guidelines pertaining to flowers that have a good nutritional composition and can effectively be eaten from wild or non-edible ornamental species that might be hazardous to human health (Benvenuti & Mazzoncini, 2021; Navarro-Gonzalez et al., 2014). This is of great importance, not only to ensure the safety of consumers but also to expand the current knowledge regarding edible flowers' toxicology and taxonomy to know which species are worth exploring for commercialization (Navarro-Gonzalez et al., 2014; Takahashi et al., 2020).

It is worth mentioning that in addition to the species, the level of toxicity also depends on the part of the plant under analysis. Some parts, such as the stems, pistils, sepals, and stamens, are commonly considered non-edible and must be carefully removed before consumption (Takahashi et al., 2020), while others can cause allergic reactions, like pollen.

Two major types of contamination are also of concern: toxic and anti-nutritional substances naturally produced by plants or external contaminations (Matyjaszczyk & Śmiechowska, 2019).

Protease inhibitors (mainly trypsin inhibitors), amylase inhibitors, tannins, antivitamin factors, hemagglutinins, saponins, cyanogenic glucosides, alkaloids, and oxalic and phytic acids are examples of anti-nutritional compounds found in some flowers (Awulachew, 2022; Kumari et al., 2021; T. C. S. P. Pires et al., 2019).

Additionally, plants can significantly absorb some heavy metals such as cadmium, which will consequently affect the viability of the species. Air contamination is also a matter of concern for their safety during consumption (Matyjaszczyk & Śmiechowska, 2019). Since edible flowers are usually consumed fresh, it is important to consider the presence of pathogens to avoid the appearance of foodborne diseases (L. Fernandes et al., 2017; Takahashi et al., 2020).

Information regarding the daily recommended doses for each species of edible flowers is still lacking (E. O. Pires, Jr., F. Di Gioia et al., 2021). Additionally, it must be considered that some edible flower species are only relevant or available in certain locations. This makes it difficult for someone who is not a native speaker to gain access to guides regarding the nutritional and anti-nutritional composition of each species and additional factors to take into consideration when conserving or preparing them to be eaten. In addition, among wild species, it is common for a flower species to have several common names. However, in some cases, different species have different chemical compositions. This may lead to misidentification, which is critical to consumers. Instead, it is recommended that, before consumption, the nutritional and anti-nutritional composition of the flower should be thoroughly analyzed (E. O. Pires, Jr., F. Di Gioia et al., 2021).

5.2. *Preservation of edible flowers*

Despite their excellent visual appeal, edible flowers have not been used in food as extensively as fresh vegetables and fruits due to their extremely short shelf-life (L. Zhao et al., 2019). The high-water content, presence of volatile compounds, and environment (moist and temperature) make them suitable for microbial growth and spoilage. These disadvantages limit the commercial use of edible flowers (Demasi, Mellano, Falla, Caser, & Scariot, 2021). At present, edible flowers must be eaten or processed within two to five days after harvest (Kou, Turner, & Luo, 2012). To retain the nutrient, bioactive and organoleptic properties, researchers, and industry are developing new technologies to process and preserve edible flowers.

Low temperature storage (Demasi et al., 2021), modified atmosphere packaging (Waghmare & Annapure, 2015), controlled atmospheric storage (Cefola, Amodio, & Colelli, 2016) are examples of storage techniques utilized for edible flowers. Regarding preservation, drying technologies are the most common and effective (Ahrné, Pereira, Staack, & Floberg, 2007). However, traditional sun drying, and hot air-drying methods have the disadvantages of long drying time, slow drying speed, and high temperature, which easily result in deterioration of color, physicochemical, and sensory attributes. At present, the most developed and extensive preservation technology used by the industry is high hydrostatic pressure (HHP) technology. As a novel non-thermal technology, it not only preserves edible flowers, but also maximizes nutrients retention (Bello, Martínez, Klotz Ceberio, Rodrigo, & López, 2014).

Edible coating technology is also one of the most promising methods to prolong the preservation time, keep the quality, ensure food safety and maintain the nutrient content of edible flowers products (Maria Leena, Yoha, Moses, & Anandharamakrishnan, 2020).

Fig. 4 illustrates the common processing and preservation methods of edible flowers.

5.3. *Functional foods with anthocyanins-rich edible flowers*

Although they can bring flavor and visual appeal to food, the ability of edible flowers to be consumed as food is still underrated, mainly due to the different challenges previously discussed herein. However, ingredients and food production from edible flowers can also be a sustainable alternative for the flower industry, as several tons of low-quality ornamental flowers are discarded every day, despite their nutritional and functional value (Rezende et al., 2019). Thus, there have been a few attempts to develop functional food products incorporated with edible flowers.

Nowadays, increased research on the bioactive and nutritive value of edible flowers has proved that they can be consumed as a whole or as processed products due to their antioxidants, fiber, and even some proteins which is benefit for health. Thus, their incorporation into food products can help to overcome the nutritional deficiencies of populations. Additionally, due to the health issue associated to the use of synthetic food additives, their replacement by natural counterparts have been undertaken by the food industry processors. Natural colorants, such as those derived from anthocyanins, are not only safe but also present several pharmacological benefits.

Rhododendron flowers aqueous extract and strawberry essence have been used to make ready-to-serve beverage, due to the its richness in antioxidant compounds (anthocyanins, phenolics and ascorbic acid) (Solanke, Chopra, & Sharma, 2016). *Delonix regia* (Red Gulmohar) flowers are a rich source of anthocyanin pigments specially cyanidin-3-*O*-rutinoside (Ramakrishnan, Akshaya, Akshitha, Dhilip Kumar, & Poorani, 2018). Other example is the use of *D. regia* aqueous extracts to perform a fortification of curd (Chhabra & Gupta, 2015). There also are some reports describing the incorporation of *Dalia mignon*, *Centaurea cyanus* L. and *Rosa damascena* petals aqueous extracts as natural additives in yogurt (Chanukya & Rastogi, 2016; Tânia C. S. P. ; Pires et al., 2018). Pires et al., used edible flowers extract as a potential substitute to the E163 commercial colorant in yogurt. It was observed that yogurts produced with flowers extracts showed similar nutritional profile and free sugar profile, thus being a suitable alternative to the additive (T. C. S. P. Pires et al., 2018). Although, the research on this area is still scarce, the applications of anthocyanin-rich edible flowers of functional foods should be a hot topic of development in a near future.

6. Conclusions and research perspectives

Despite cultural differences and consumption patterns, edible

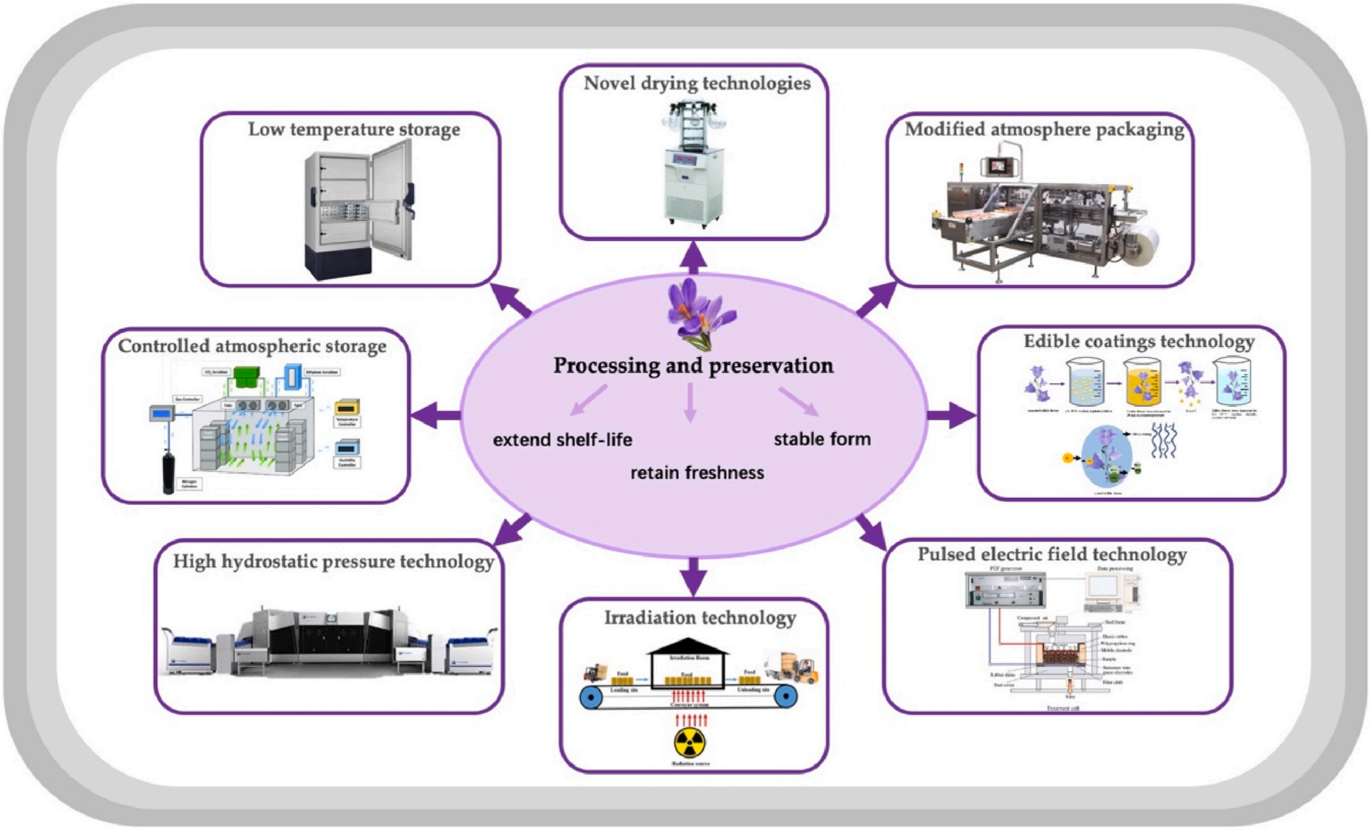


Fig. 4. Common processing and preservation methods used for Edible Flowers.

flowers seem to represent an attractive option for new food trends, with potential health benefits worldwide.

In general, edible flowers show an interesting macro and micronutrient composition. Their phytochemical composition, and particularly anthocyanins, is often related to their colors and bioactivity. In fact, anthocyanin-rich edible flowers have shown to be promising species for consumption due to the properties herein discussed. However, more studies focusing on these types of flowers are needed to strengthen the position of such cultivars.

Anthocyanin-rich edible flowers have been described as possessing bioactive properties in different contexts. Nevertheless, several challenges are associated with their consumption, namely, toxicity issues, and the presence of anti-nutritional substances and pathogens. For this reason, preservation of edible flowers is also a matter of concern, novel non-thermal processing and preservation methods that minimize the sensory, nutritional, and bioactive properties losses and prolong shelf-life should be preferred. These methods meet the needs of consumers looking for minimally processed foods that are closer to fresh products and do not use chemical preservatives.

Also, more research on how these anthocyanin food sources may be incorporated in the diet is crucial. Although they can bring flavor and visual appeal to food, the ability of edible flowers to be consumed as food is still underrated, mainly due to the different challenges discussed herein. For instance, their incorporation in processed foods needs to be investigated as only a small number of studies have been performed so far on this matter.

Therefore, studies focusing on the gastrotechnic and food processing properties of these flowers will be an emerging topic, to understand the ideal way to consume them with the maximum nutritional and bioactive outcomes and allowing the development of different types of nutraceuticals and functional foods to meet the nutritional needs of individuals.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tifs.2023.07.010.

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