Phytochemical potential of berries: An overview
Potencial fitoquímico de las bayas: Una descripción general
Potencial fitoquímico de bagas: uma visão geral

Talison Roberto Maurer[a], Carolina Zuanazzi Tonello[a], Bianca Oliveira Machado[a], Thomas dos Santos Trentin[b], Charise Dallazem Bertol[c,d], Nadia Canali Lângaro[a, e], José Luís Trevizan Chiomento[a, e*]

[a] Graduate Program in Agronomy, University of Passo Fundo, Passo Fundo, RS, Brazil.

[b] Graduate Program in Soils and Plant Nutrition, University of São Paulo, Piracicaba, SP, Brazil.

[c] Undergraduate Program in Pharmacy, University of Passo Fundo, Passo Fundo, RS, Brazil.

[d] Graduate Program in Human Aging, University of Passo Fundo, Passo Fundo, RS, Brazil.

[e] Undergraduate Program in Agronomy, University of Passo Fundo, Passo Fundo, RS, Brazil.

[*] Corresponding autor: jose-trevizan@hotmail.com

Para citar este artículo: Maurer, T., Tonello, C., Machado, B., Trentin, T., Bertol, C., Lângaro, N. & Chiomento, J. L. (2023). Phytochemical potential of berries: An overview. *LADEE*, 4(1), 11–28. https://doi.org/10.17981/ladee.04.01.2023.2

Abstract

Introduction: Phytochemicals, or secondary metabolites, present in small fruits are responsible for improving the health of consumers when included in the daily diet. All edible forms of berries are considered safe functional foods because they have nutritional properties and therapeutic potential. **Objective**: Therefore, this narrative review aims to analyze the state of the art on the phytochemical potential of the six main small fruits (blackberry, physalis, raspberry, blueberry, strawberry and grape), to gather information on the application of strategies to obtain berries with higher concentrations of biomolecules and to present the benefits of phytochemicals to the consuming public. **Methodology**: In the first stage of this narrative review, the cultivation scenario of these six main berries is contextualized. Subsequently, a temporal metasynthesis on berry phytochemicals is performed. In the last part of this review, we detail the biomolecule profile of blackberry, physalis, raspberry, blueberry, strawberry and grape and focus on their action against diseases. **Results**: The consumption of these six berries triggers anti-diabetic, anti-inflammatory, anti-cancer, anti-aging, anti-obesity, anti-microbial, anti-ulcer and radioprotective, neuroprotective and glucoregulatory actions. Despite scientific and clinical evidence on the positive effects of small fruit consumption on human health, their consumption remains low. **Conclusions**: The creation of public policies will contribute to improve the scenario of berry intake because it will involve the entire small fruit production chain: scientists, producers, food and pharmaceutical industries, and consumers.

Keywords: Fruticulture; small fruits; secondary metabolites; biomolecules

Resumen

Introducción: Los fitoquímicos, o metabolitos secundarios, presentes en las frutas pequeñas son los responsables de mejorar la salud de los consumidores cuando se incluyen en la dieta diaria. Todas las formas comestibles de bayas se consideran alimentos funcionales seguros porque tienen propiedades nutricionales y potencial terapéutico. **Objetivo:** Por lo tanto, esta revisión narrativa tiene como objetivo analizar el estado del arte sobre el potencial fitoquímico de los seis principales frutos pequeños (mora, physalis, frambuesa, arándano, fresa y uva), para recopilar información sobre la aplicación de estrategias que permitan obtener bayas con mayores concentraciones de biomoléculas y presentar los beneficios de los fitoquímicos al público consumidor. **Metodología:** En la primera etapa de esta revisión narrativa, se contextualiza el escenario de cultivo de estas seis bayas principales. Posteriormente, se realiza una metasíntesis temporal sobre fitoquímicos en bayas. En la última parte de esta revisión, se detalla el perfil de biomoléculas de mora, physalis, frambuesa, arándano, fresa y uva y nos enfocamos en su acción contra las enfermedades. **Resultados:** El consumo de estas seis bayas desencadena acciones antidiabéticas, antiinflamatorias, anticancerígenas, antienvejecimiento, antiobesidad, antimicrobianas, antiulcerosas y radioprotectoras, neuroprotectoras y glucorreguladoras. A pesar de las evidencias científicas y clínicas sobre los efectos positivos del consumo de frutos pequeños en la salud humana, su consumo sigue siendo bajo. **Conclusiones**: La creación de políticas públicas contribuirá a mejorar el escenario de la ingesta de berries porque involucrará a la totalidad de la cadena productiva de la pequeña fruta: científicos, productores, industrias alimenticia y farmacéutica y consumidores.

Palabras clave: Fruticultura; frutos pequeños; metabolitos secundarios; biomoléculas

Resumo

Introdução: Os fitoquímicos, ou metabolitos secundários, presentes nos pequenos frutos são responsáveis por melhorar a saúde dos consumidores quando incluídos na dieta diária. Todas as formas comestíveis de bagas são consideradas alimentos funcionais seguros, pois possuem propriedades nutricionais e potencial terapêutico. **Objetivo**: Assim, esta revisão narrativa tem como objetivo analisar o estado da arte sobre o potencial fitoquímico dos seis principais pequenos frutos (amora, physalis, framboesa, mirtilo, morango e uva), reunir informação sobre a implementação de estratégias para a obtenção de bagas com maiores concentrações de biomoléculas e apresentar os benefícios dos fitoquímicos ao público consumidor. **Metodologia**: Na primeira fase desta revisão narrativa, contextualiza-se o cenário de cultivo destas seis principais bagas. Segue-se uma meta-síntese temporal dos fitoquímicos presentes nas bagas. Na última parte desta revisão, detalhamos o perfil de biomoléculas da amora, physalis, framboesa, mirtilo, morango e uva e focamos a sua ação contra doenças. **Resultados**: O consumo destas seis bagas desencadeia acções anti-diabéticas, anti-inflamatórias, anti-cancerígenas, anti-envelhecimento, anti-obesidade, anti-microbianas, anti-úlcera e radioprotectoras, neuroprotectoras e glucoreguladoras. Apesar das evidências científicas e clínicas sobre os efeitos positivos do consumo de pequenos frutos na saúde humana, o seu consumo continua a ser baixo. **Conclusões**: A criação de políticas públicas contribuirá para melhorar o cenário de consumo de frutos vermelhos, pois envolverá toda a cadeia produtiva dos pequenos frutos: cientistas, produtores, indústrias alimentícias e farmacêuticas e consumidores..

Palavras-chave: Fruticultura; pequenos frutos; metabólitos secundários; biomoléculas

DOI: 10.17981/ladee.04.01.2023.2

Fecha de recibido 1/02/2023. Fecha de aceptado 29/02/2023.

LADEE vol. 4 no. 1, pp. 11–28. January - June, 2023
Barranquilla. e-ISSN 2744-9750 (En línea)

1. Introduction

Fruit growing represents one of the segments that has stood out in Brazilian agribusiness. In 2021 Brazil produced about 41.3 million tons of fruit. In financial terms, this production represents R$ 49.8 billion and represents a total cultivated area of more than 4.2 million hectares (Kist et al., 2022). Brazil occupies the third position in the ranking of the largest fruit producers in the world, behind only China and India. Orange [*Citrus sinensis* (L.) Osbeck], banana (*Musa* spp.) and grape (*Vitis vinifera* L.) are among the most produced fruits in the country in the 2022 harvest. Along with the grape, other small fruits, also called berries, are increasingly participating in the diet of Brazilians. Due to the favorable climate, commercialization potential and benefits to consumers' health, the cultivation of blackberry (*Rubus* spp.), goldenberry (*Physalis peruviana* L.), raspberry (*Rubus idaeus* L.), blueberry (*Vaccinium* spp.) and strawberry (*Fragaria X ananassa* Duch.) is consolidating in different regions of Brazil.

In the current scenario, consumers are increasingly demanding when purchasing foods with the potential to benefit their health, and the presence of complex mixtures of phytochemicals in fruit plants is a characteristic that contributes to the increase in the consumption of berries. Hundreds or even thousands of these Secondary Metabolites (SM) can be detected in a single tissue sample. These phytochemicals have physiological properties linked to the sensory attributes of the fruits (aroma, flavor and color) and which act in the plant's defense against abiotic and biotic stresses (Lara et al., 2020).

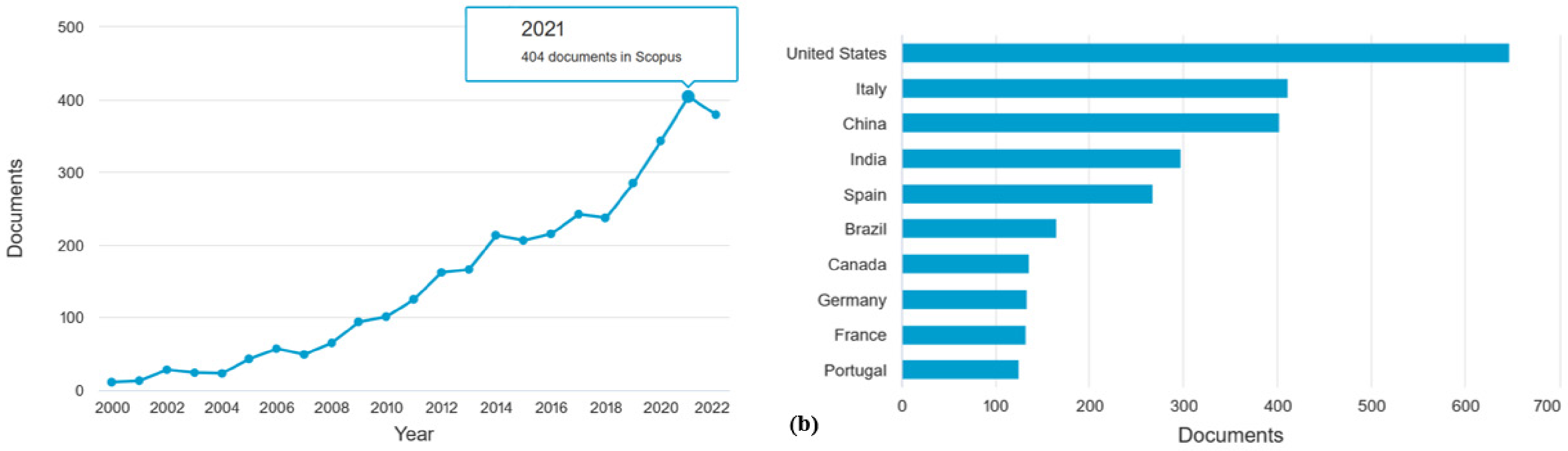
Among fruiting crops, berries have attracted great attention due to their wide spectrum of functional activities, resulting from the presence of their bioactive compounds. The small fruits contain SM that contribute to reducing the risk of non-transmissible chronic diseases, such as flavonoids (anthocyanins and ellagic acid) and stilbene. Fruits with higher amounts of bioactive compounds belong to the botanical families Ericaceae (blueberry), Grossulariaceae (currant), Rosaceae (blackberry, raspberry and strawberry) and Vitaceae (grape) (Skrovankova et al., 2015). Knowing berries phytochemical composition, understanding the factors that influence their biosynthesis and studying their protective effects on plants and human health will help fruit growers to establish phytotechnical, phytosanitary and nutritional practices that enhance SM levels.

Therefore, this narrative review aims to analyze the phytochemical potential of small fruits (blackberry, goldenberry, raspberry, blueberry, strawberry and grape), their benefits to the consumer public and compile information on the main phytochemicals found in these berries.

2. Metasynthetic time-clip on berries phytochemicals

The Scopus database (https://www.scopus.com) was searched for publications available in the last 22 years (2000-2022) on berry biomolecules. Using "phytochemicals", "secondary metabolites", "berries", "blackberry", "goldenberry", "raspberry", "blueberry", "strawberry" and "grape" as keywords and AND (inclusion) and OR (scope) as logical search operators. The full syntax used was: phytochemicals OR secondary metabolites AND berries OR blackberry OR goldenberry OR raspberry OR blueberry OR strawberry OR grape. We found 3 485 papers and found that 2 021 had the highest scientific output on the topic (Fig. 1a) and that the United States dominates the research on this topic (Fig. 1b).

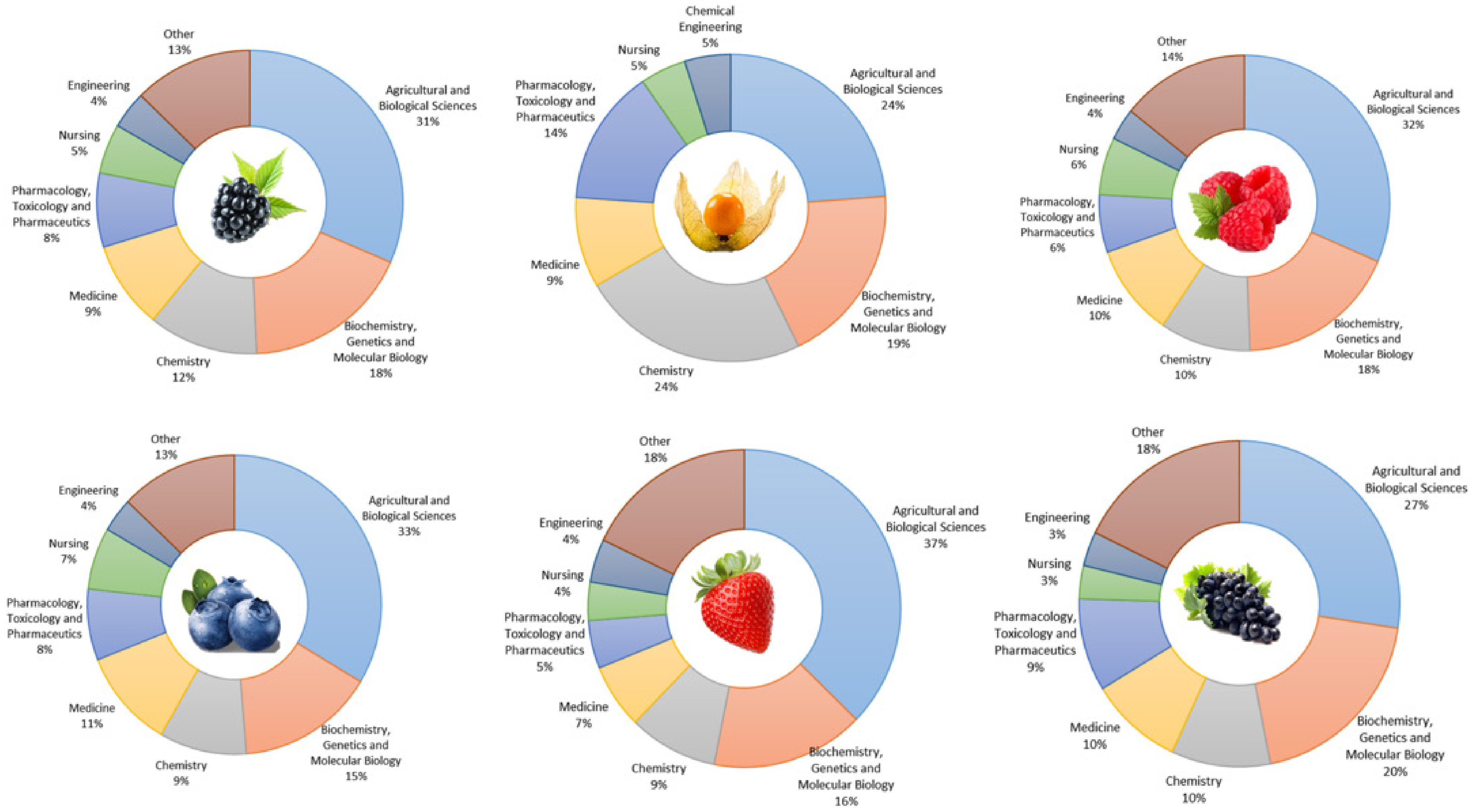
Fig. 1. Number of papers per year (a) and per country (b) on berry biomolecules.



Source: Scopus database.

Also, the most recurrent areas of SM research on small fruits were also looked at. In this case the syntax used was: phytochemicals OR secondary metabolites AND each berry (blackberry, goldenberry, raspberry, blueberry, strawberry, grape). The highlighted areas were “Agricultural and Biological Sciences”, “Biochemistry, Genetics and Molecular Biology”, “Chemistry” and “Medicine” (Fig. 2).

Fig. 2. Major research areas involving phytochemicals in berries (blackberry, goldenberry, raspberry, blueberry, strawberry and grape).

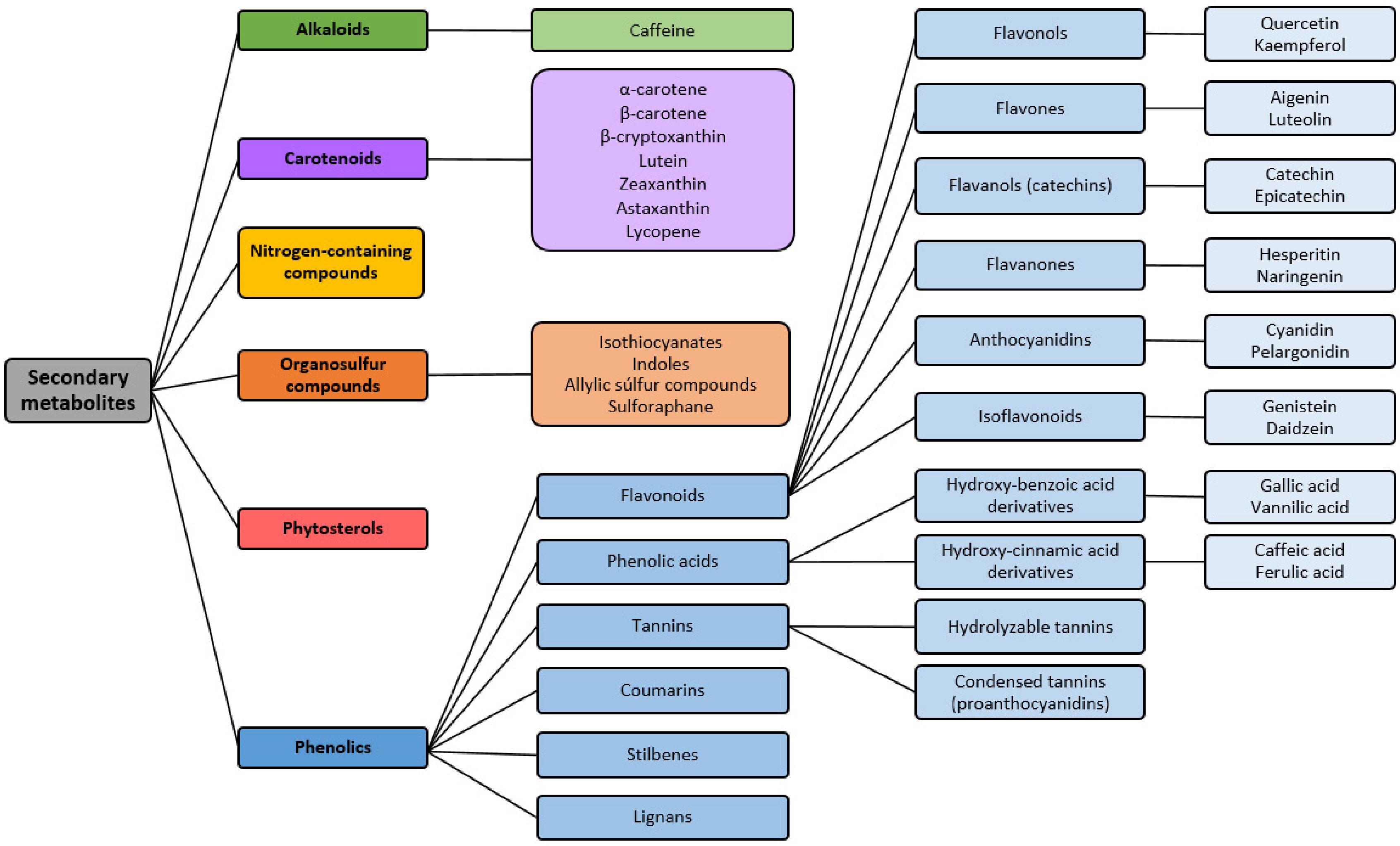


Source: Own authorship.

3. *Biosynthesis, interactions and benefits of berry phytochemicals*

Approximately 200 000 SM are known and about 20 000 of them originate from horticultural and grain crops. SM in plants are classified into six main groups (Fig. 3): 1) alkaloids; 2) carotenoids; 3) nitrogen-containing compounds; 4) organosulfur compounds; 5) phenolics; 6) phytosterols (Liu, 2004; Monjotin et al., 2022). Fundamentally, metabolite biosynthetic pathways are conserved in most plants, with a large proportion of Primary Metabolites (PM) found in all plant tissues. PM are critical precursors of SM. SM can be biosynthesized by the pathways: 1) mevalonic (terpenes); 2) shikimate (phenolic compounds); 3) tricarboxylic acid cycle (nitrogen-containing compounds) (Jamwal et al., 2018). However, the biosynthesis and accumulation of SM depends on genetic (mainly), physiological, edaphoclimatic and biogeographic aspects and also on management and cultural treatments applied to fruiting plants.

Fig. 3. Classification of dietary phytochemicals.



Source: According to Liu (2004) and Monjotin et al. (2022).

Studying the phytochemical potential of nine strawberry cultivars (Chiomento, Lima Junior et al., 2021), showed that the total contents of anthocyanins, flavonoids, and polyphenols were dependent on genetic background. Similarly, Cvetković et al. (2022) reported that total anthocyanin and phenolic contents and radical scavenging activity differed among three blueberry cultivars. On the other hand, osmotic stress was also found to be a regulatory agent of anthocyanin production in grapevine (Tuteja & Mahajan, 2007). In addition to genotype and abiotic stresses, agronomic practices also alter the phytochemical quality of fruit. Johnson (2002) demonstrated that in the organic growing system strawberries rich in ascorbic acid and phenolic compounds and with higher antioxidant activity were produced, compared to the conventional system.

Generally, higher SM contents are seen in plants subjected to stresses, which includes elicitors or signaling molecules (Ramakrishna and Ravishankar, 2011), because the plant needs to produce specific SM, in quantity and quality, to combat stressful factors (Pant et al., 2021). Physiologically, the production of phytochemicals can increase in stressed plants because growth is more inhibited relative to photosynthesis and this allocates the fixed carbon (C) mostly to SM. The synthesis of these phytochemicals provides plants with the ability to protect themselves against environmental stresses and perform interactions in structural and functional stabilization through signaling processes and pathways (Isah, 2019). The production of phytochemicals is a plant defense response because many SM confer protection against abiotic (light, temperature, salinity) and biotic (herbivores and phytopathogens) stresses.

Some strategies can contribute to improve the accumulation of biomolecules in berries, such as the use of plant biostimulants, which can create stressful conditions to the plant and this will increase the activity of its secondary metabolism. Garcia-Seco et al. (2015) reported that the use of the rhizobacterium *Pseudomonas fluorescens* increased the concentration of flavonoids in blackberry. The use of *Ascophyllum nodosum* algae extract and alfalfa (*Medicago sativa* L.) based protein hydrolysates improved the content of phenolic compounds in strawberry (Soppelsa et al., 2019). In this same horticultural crop, the use of on-farm monospecific mycorrhizal inoculant (*Claroideoglomus etunicatum* species) enhanced the total contents of anthocyanins, flavonoids and polyphenols (Chiomento, De Nardi et al., 2021).

In addition to providing protection to plants, SM play a key role in the health of berry consumers. On a global scale, dietary recommendations include the consumption of horticultural crops as a disease prevention strategy, because these organs (roots, stems, leaves and fruits, mainly), in addition to their fiber and macro and micronutrient content, carry phytochemicals that stand out for their antioxidant properties and free radical scavenging potential (Di Lorenzo et al., 2021).

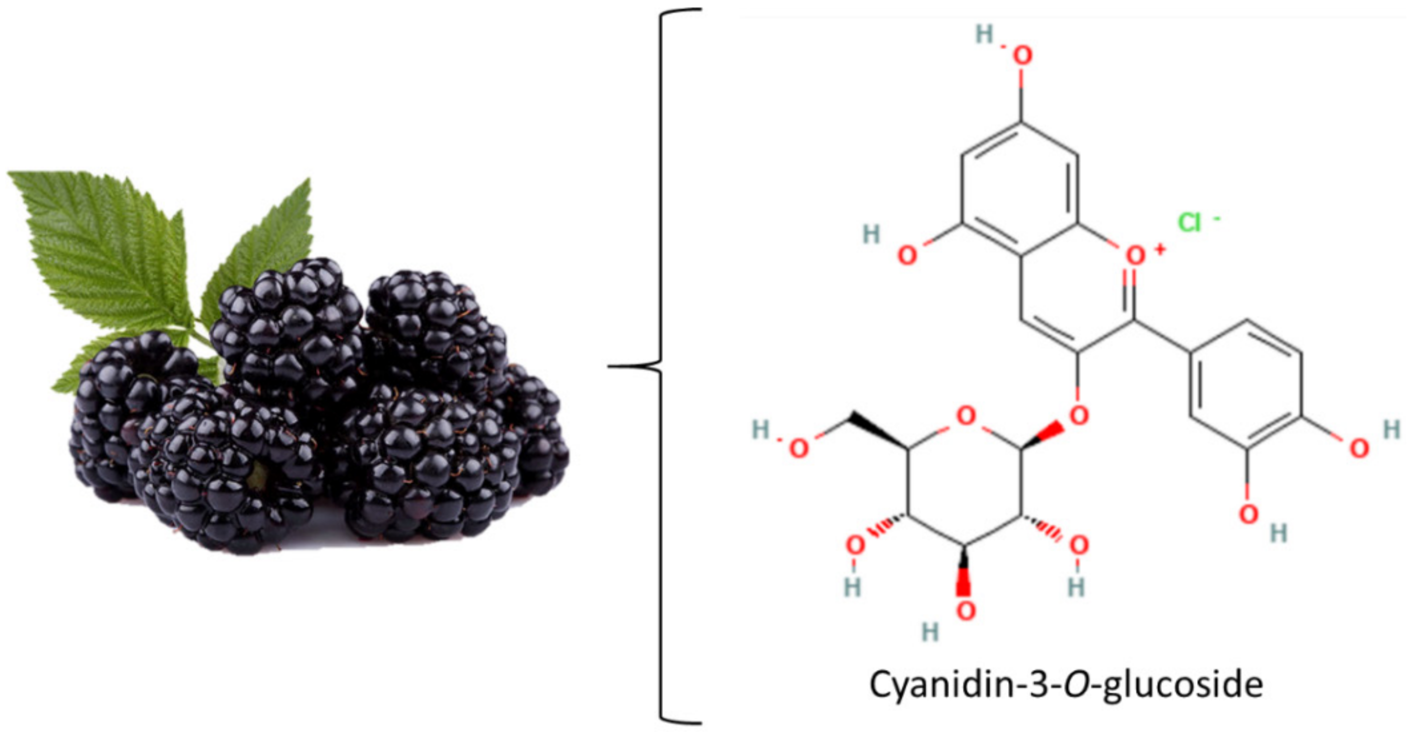
The literature indicates that the intake of foods rich in phytochemicals works as an anti-inflammatory agent, anticarcinogenic (Liu, 2013), and has cardiovascular and chemopreventive action (De Pascual-Teresa et al., 2010). These foods are considered functional because, besides nourishing, they present beneficial properties to health and this helps in the prevention of diseases. From here, we grouped the literature according to berries (blackberry, goldenberry, raspberry, blueberry, strawberry and grape) to point out some results on the beneficial effects of SM to human health.

3.1. *Blackberry*

The increase in blackberry consumption is mainly linked to its phytochemical properties, such as phenolics and carotenoids, with a preventive health action. This berry contains numerous antioxidants, such as ascorbic acid, phenols, ellagic acid, ellagitannins and flavonoids, represented by anthocyanins (Clifford & Scalbert, 2000).

Anthocyanins are the phenolic compounds responsible for the purple coloration of blackberries, increase their accumulation in line with the fruit ripening. The typical purplish/black color of blackberries also constitutes with an attractive to the fruit consumption (Acosta-Montoya et al., 2010). The main SM present in blackberries is an anthocyanin, cyanidin-3-*O*-glucoside (Fig. 4) (Ferreira et al., 2010).

Fig. 4. Cyanidin-3-O-glucoside is the main phytochemical present in blackberry. This biomolecule has a beneficial action on cardiovascular health and anticancer.



Source: Own authorship. The molecular structure was obtained from the National Center for Biotechnology Information (https://pubchem.ncbi.nlm.nih.gov/compound/Cyanidin-3-O-glucoside).

Other SM also detected in blackberry include: kaempferol-3-(6-acetylgalactoside), kaempferol-3-*O*-glycoside, quercetin-3-galactoside, quercetin-3-galactoside, quercetin-3-glycoside, quercetin-3-rutinoside, quercetin-3-ramnoside, myricetin-3-galactoside, myricetin-3-glycoside, cyanidin-3-rutinoside, cyanidin-3-arabinoside, pelargonidin-3-*O*-glycoside, peonidin-3-*O*-glycoside, ellagic acid, sanguiin H-6, lambertianin C, gallic acid, galloyl esters, *p*-coumaric acid, and coumaroyl glycosides (Gancel et al., 2011; Kolniak-Ostek et al., 2015).

Human clinical studies have reported the benefits of cyanidin-3-*O*-glucoside: anti-inflammatory, antiviral, antiproliferant, and anticarcinogenic properties (Knobloch et al., 2016). The hydroxyl groups enable anthocyanins to act as free radical scavengers, helping to neutralize reactive oxygen species and protect cells from oxidative damage (Giusti & Jing, 2007). The ability to chelate metal ions further contributes to their antioxidant activity.

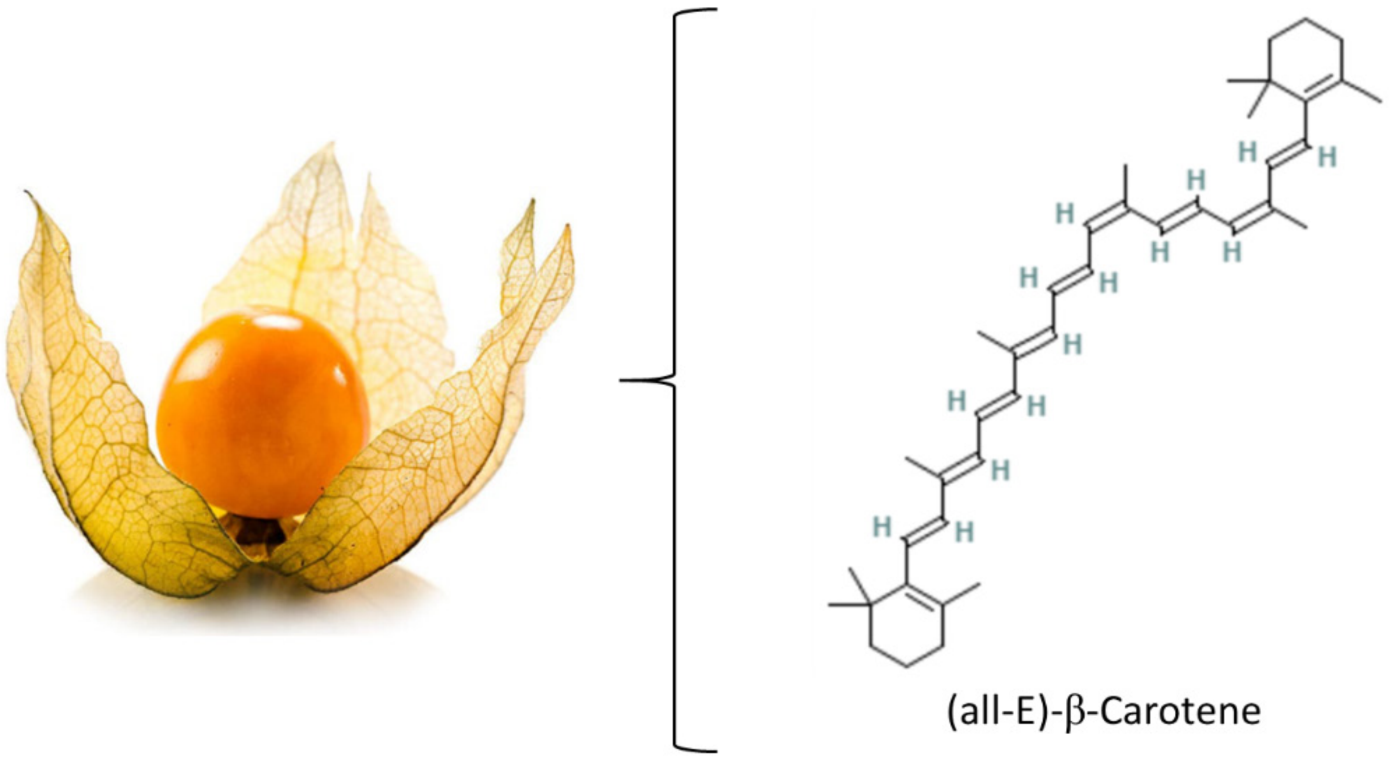
Epidemiological studies have provided evidence that blackberry consumption aids in reducing degenerative diseases, decreases the risk of cardiovascular diseases, and provides anti-obesity, anticancer, antidiabetic, antimicrobial, neurodegenerative, anti-inflammatory, and anti-ulcer effects (Gowd et al., 2018). Blackberry extract has an anticancer effect, which is mainly due to blocking Activator Protein 1 (AP-1) that is reconciled from Reactive Oxygen Species (ROS) and activation of protein kinase enzyme by mitogen (Feng et al., 2004). ROS are responsible for premature aging, which can cause ischemia reperfusion damage, inflammatory and degenerative diseases, cancer, and Deoxyribonucleic Acid (DNA) damage; consuming fruits with antioxidants reduce these substances (Joshipura et al., 2001).

3.2. *Goldenberry*

Although goldenberry is a fruit with healthy properties, as it is rich in vitamin A and C, iron, phosphorus, flavonoids, alkaloids, and phytosteroids, this horticultural crop is underutilized in the current food production system, which includes its nutritional benefits (Muñoz et al., 2021). Recently, goldenberry has been included in the list of the "superfruit" family as a marketing strategy to promote the health benefits arising from the fruits of this horticultural crop with less popularity worldwide, but containing many phytochemicals (Mazova et al., 2020).

The SM present in this berry are responsible for the characteristics such as the color and flavor of the fruit, as well as being responsible for the antioxidant activity. For example, ß-carotene, which gives the fruit its orange coloration, plays an important role in vision, cell division and differentiation, and reproduction in humans. The main SM present in goldenberry is a carotenoid, (all-E)-ß-carotene (Fig. 5) (Etzbach et al., 2018).

Fig. 5. (all-E)-ß-carotene is the main phytochemical present in goldenberry. This SM plays an important role in human vision.



Source: Own authorship. The molecular structure was obtained from the National Center for Biotechnology Information (https://pubchem.ncbi.nlm.nih.gov/compound/All-E_-beta-Carotene#section=2D-Structure).

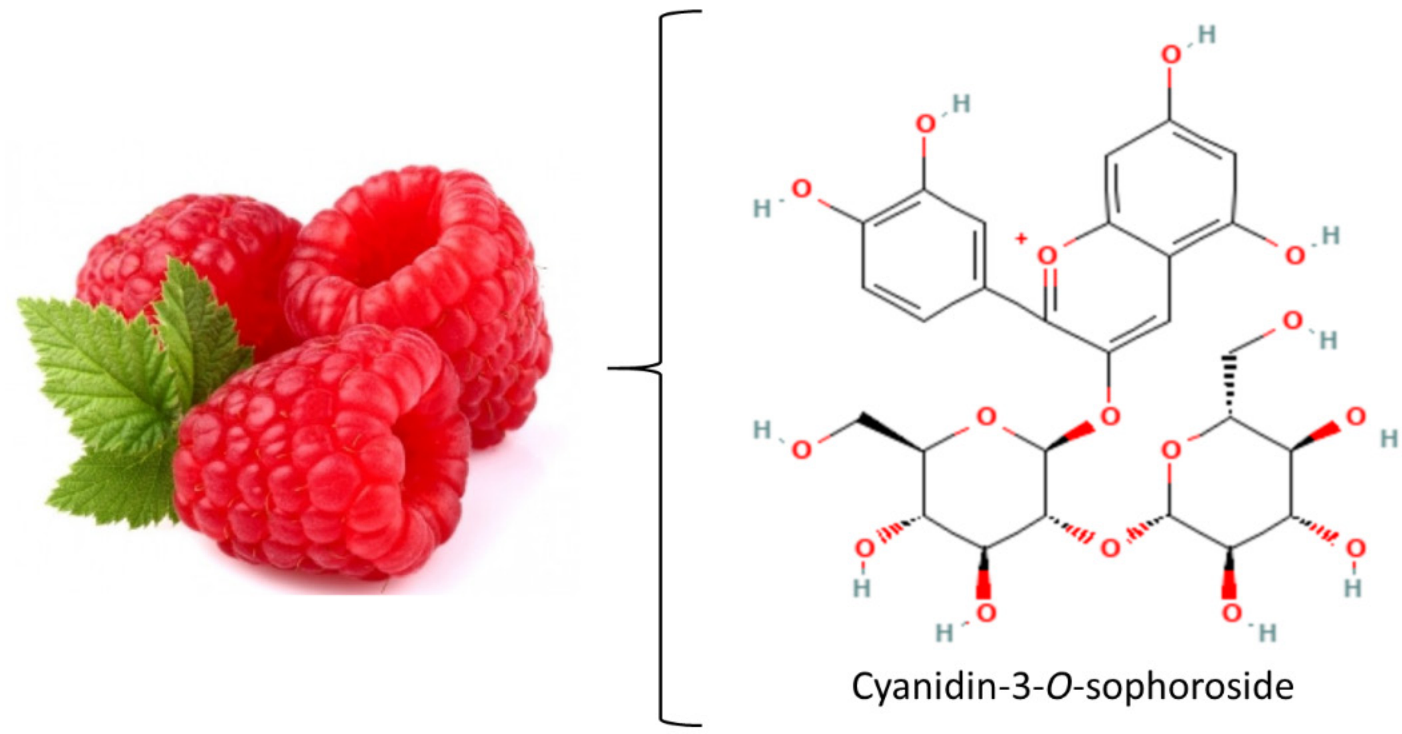
Other SM also detected in goldenberry include: (-)-caryophyllene oxide, (5á)-pregnane-3,20á-diol, (9Z)-ß-carotene, all-trans-ß-carotene, 9-cis-ß-carotene, (all-E)-lutein, (all-E)-lutein 3’-*O*-palmitate, (all-E)-lutein 3-*O*-myristate, (all-E)-lutein 3-*O*-palmitate-3’-*O*-myristate, (all-E)-lutein dimyristate, (all-E)-lutein dipalmitate, (all-E)-neoxanthin, (all-E)-neoxanthin dipalmitate, (all-E)-neoxanthin myristate, (all-E)-neoxanthin palmitate, (all-E)-taraxanthin, (all-E)-taraxanthin ester, (all-E)-violaxanthin, (all-E)-violaxanthin dimyristate, (all-E)-violaxanthin dipalmitate, (all-E)-violaxanthin myristate-palmitate, (all-E)-zeaxanthin dimyristate, (all-E)-zeaxanthin dipalmitate, (all-E)-zeaxanthin myristate-palmitate, (all-E)-zeinoxanthin, (all-E)-α-carotene, (all-E)-α-cryptoxanthin, (all-E)-α-cryptoxanthin myristate, (all-E)-α-cryptoxanthin palmitate, quercetin dihydrate, catechin, rutin, epicatechin, myricetin and kaempferol (Olivares-Tenorio et al., 2017; Etzbach et al., 2018).

The literature reports that there are specific bioactive phytochemicals in goldenberry. Among them are withanolides, which are C28 ergostane-type steroids with oxygenation in the steroid skeleton in which C-26 and C-22, or C-26 and C-23, are oxidized to produce δ- or γ-lactone. These compounds possess antimicrobial, anticancer, anti-inflammatory, antidiabetic, hypocholesterolemic, and immunomodulatory activity (Yamika et al., 2019). Withanolide E and 4ß-hydroxywithanolide E, specifically, have anticancer effects. In addition to withanolides, phthalins are pseudosteroids isolated and characterized from the *Physalis* genus, for example phthalin A, B, D, F and glycoside present in *P. peruviana*, which play anticancer, antioxidant and anti-inflammatory activities (Zhang, Deng et al., 2013).

3.3. *Raspberry*

Raspberry contains numerous bioactive compounds, such as phenolics, organic acids and minerals (Chen et al., 2013). In addition to being rich in vitamin C and dietary antioxidants, raspberry has a high ellagitannin content, which results in the release of free ellagic acid during hydrolysis (Rao & Snyder, 2010). In addition, raspberry has a unique anthocyanin profile, with cyanidin-3-*O*-soforoside being the main SM present in this berry (Fig. 6) (Burton-Freeman et al., 2016). Although all berries have cyanidin-based anthocyanins, not all share similar glycosidic units. The soforoside unit, for example, is a cyanidine glycoside unique to raspberries (Torre & Barritt, 1977).

Fig. 6. Cyanidin-3-*O*-soforoside is the major phytochemical present in raspberry.



Source: Own authorship. The molecular structure was obtained from the National Center for Biotechnology Information (https://pubchem.ncbi.nlm.nih.gov/compound/Cyanidin-3-O-sophoroside#section=2D-Structure).

Other SM also detected in raspberries include: ellagic acid (and its glycosides), ellagitannins, sanguiin H-6, lambertianin C, caffeic acid, ferulic acid, p-coumaric acid, p-hydroxybenzoic acid, sinapic acid, cinnamic acid, vanillic acid, coumaroyl glycosides, cyanidin-3,5-diglucoside, cyanidin-3-(2^{G}-glucosylrutinoside), cyanidin-3-O-glucoside, cyanidin-3-O-rutinoside, pelargonidin-3-O-sophoroside, pelargonidin-3-(2G-glucosylrutinoside), pelargonidin-3-O-glucoside, pelargonidin-3-O-rutinoside, kaempferol-glucuronide, kaempferol-hexoside, quercetin-3-glucuronide, quercetin-3-rutinoside, quercetin-3-hexoside, quercetin-3-ramnoside, quercetin-3-glucoside, apigenin, chrysin and naringenin (Rao & Snyder, 2010; Chen et al., 2013; Maksimović et al., 2013; Diaconeasa et al., 2014).

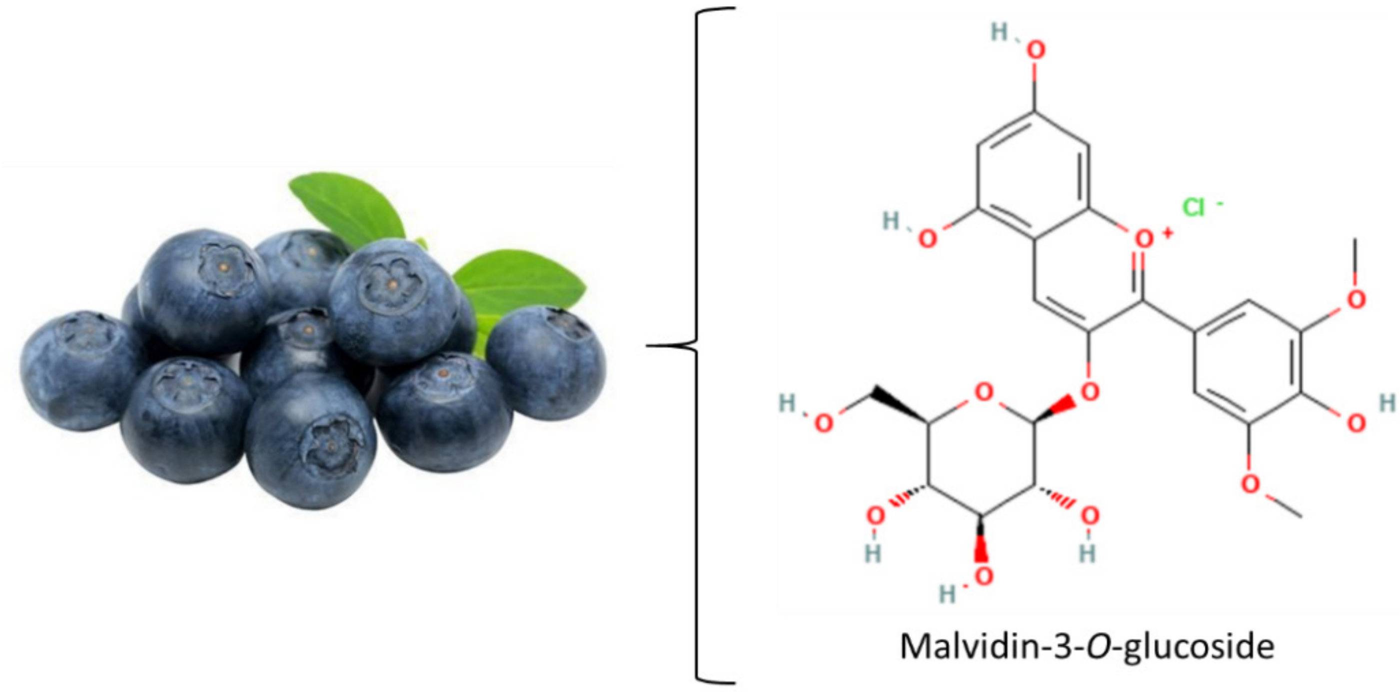
The literature reports that raspberry extracts had anticoagulant and fibrinolytic action in an *in vitro* assay (Torres-Urrutia et al., 2011). In *in vivo* mouse studies, Ding et al. (2014) suggested that the use of ellagitannin-rich fractions provides improvements in endothelial function, which could reduce the risk of hypertension and atherosclerotic development. In parts this is due to reduced oxidative stress and inflammation in vascular tissue after feeding mice with ellagic acid, since the effects of ellagic acid stem from activation of erythroid nuclear factor 2 and increased endothelial nitric oxide synthase activity.

Ellagic acid, present in raspberries, is an inhibitor of melanin production (Draelos et al., 2013), due to inhibition of melanocyte proliferation and melanin synthesis by the enzyme tyrosinase (Yoshimura et al., 2005), presenting great potential as a cosmetic in the treatment of hyperchromia. Other studies with raspberry extracts/fractions evidenced antioxidant and anti-inflammatory activity *in vitro*, lipid peroxidation (Kähkönen et al., 2012), and increased activity of antioxidant enzymes, such as catalase and superoxide dismutase (Sangiovanni et al., 2013). In addition, Liu et al. (2010) showed that a raspberry-rich diet can suppress diethylnitrosamine-induced liver lesions in rats and reduce the definitive diagnostic features of the neoplasm.

3.4. *Blueberry*

The blueberry is widely studied for its high phytonutrient content, mainly phenolic compounds (Felgus-Lavefve et al., 2022), biomolecules responsible for popularizing this berry as a "superfruit" due to its antioxidant capacity (Kalt et al., 2020). This antioxidant capacity depends on anthocyanins, procyanidins, chlorogenic acid, and flavonoids (Wang et al., 2022). Among SM, anthocyanins are the most important subclass of antioxidant substances and are linked to the fruit coloration, which plays a role in its acceptance by consumers. In all, 15 types of anthocyanins have been identified in blueberries, including delphinidin, petunidin, peonidin, cyanidin, and malvidin (Chai et al., 2021). Of these, malvidin-3-*O*-glycoside is the major SM present in blueberry (Fig. 7) (Wang et al., 2022).

Fig. 7. Malvidin-3-*O*-glycoside is the major blueberry secondary metabolite.



Source: Own authorship. The molecular structure was obtained from the National Center for Biotechnology Information (https://pubchem.ncbi.nlm.nih.gov/compound/Malvidin-3-Glucoside#section=2D-Structure).

Others SM also found in blueberry include: cyanidin-3-*O*-galactoside, cyanidin-3-*O*-glucoside, cyanidin-3-*O*-arabinoside, delphinidin-3-*O*-galactoside, delphinidin-3-*O*-arabinoside, delphinidin-3-*O*-glucoside, malvidin-3-*O*-galactoside, malvidin-3-*O*-arabinoside, petunidin-3-*O*-galactoside, petunidin-3-*O*-arabinoside, petunidin-3-*O*-(6"-acetyl-glucoside), peonidin-3-*O*-galactoside, peonidin-3-*O*-arabinoside, myricetin-3-*O*-glucoside, myricetin-3-*O*-rhamnoside, quercetin-3-D-galactoside, quercetin-3-*O*-glucoside and quercetin-3-*O*-rutinoside (Buran et al., 2014; Correa-Betanzo et al., 2015).

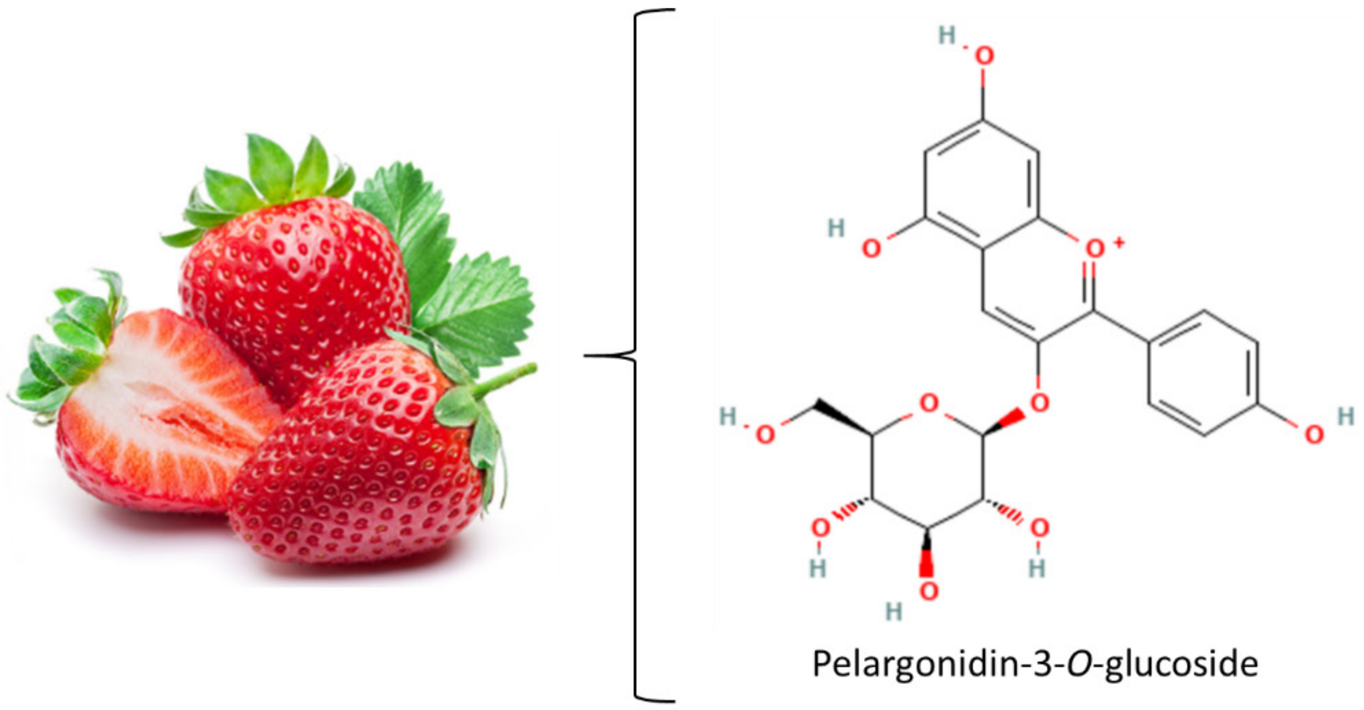
Among the benefits of blueberry consumption are its anti-inflammatory and antioxidant actions and its effects on vascular and glucoregulatory function. The literature reports that blueberry consumption (approximately one-third cup) decreases the risk of type 2 diabetes mellitus, retinal stress, inflammation, and cardiovascular and neurological diseases. These positive effects are linked to the daily consumption of anthocyanins (50 mg) present in the fruit (Kalt et al., 2020).

For example, anthocyanins present in blueberries inhibited IFN-γ receptor 2, which is responsible for signal transduction transmitted by pro-inflammatory cytokines (Roth et al., 2016). Blueberry extracts conferred protection against DNA damage induced by hydroxide peroxide and tert-butylhydroperoxide (Van Breda et al., 2018). Blueberry consumption decreases Low-Density Lipoprotein (LDL-C), triglycerides, and adiponectin and increases High-Density Lipoprotein (HDL-C) (Li et al., 2015), due to modulation of glucose metabolism (Reis et al., 2016), and effects on endothelium composition (Kalea et al., 2006). Anthocyanins constituents of blueberries increase the viability and differentiation of human corneal epithelial cells (Song et al., 2010).

3.5. *Strawberry*

Appreciated for its characteristic aroma and flavor and distributed in various agroecosystems, strawberry is the main cultivated species among small fruits (Chiomento et al., 2023). In addition to palatable properties, strawberries have high antioxidant activity that is attributed to phenolic compounds, mainly anthocyanins. Besides being responsible for the typical strawberry red coloration, anthocyanins have beneficial effects on human health (Chiomento, Lima Junior et al., 2021). No wonder that the main SM constituent of strawberry is an anthocyanin, pelargonidin-3-*O*-glycoside (Fig. 8) (Duarte et al., 2018).

Fig. 8. Pelargonidin-3-*O*-glycoside is the major strawberry phytochemical.



Source: Own authorship. The molecular structure was obtained from the National Center for Biotechnology Information (https://pubchem.ncbi.nlm.nih.gov/compound/Pelargonidin-3-glucoside#section=2D-Structure).

Others detected strawberry’s SM include: cyanidin-3-*O*-glucoside, cyanidin-3-*O*-rutinoside, cyanidin-3-*O*-galactoside, cyanidin-3-malonylglucoside, pelargonidin-3-*O*-rutinoside, pelargonidin-3-*O*-galactoside, pelargonidin-3-*O*-arabinoside, pelargonidin-3-malonylglucoside, pelargonidin-3-malylglucoside, peonidin-3-*O*-glucoside, kaempferol-3-glucoside, kaempferol-3-glucuronide, kaempferol-3-malonylglucoside, kaempferol 3-O-(3”,6”-*O*-di-*p*-coumaroyl)-glucoside, quercetin-3-glucuronide, quercetin-3-malonylglucoside, quercetin-3-rutinoside, quercetin-3-glucoside, ellagic acid, gallic acid, ellagitannin, galotannin, caffeic acid, *p*-coumaric acid, agrimoniin and lambertianin (Giampieri et al., 2014; Howard et al., 2014; Chaves et al., 2017).

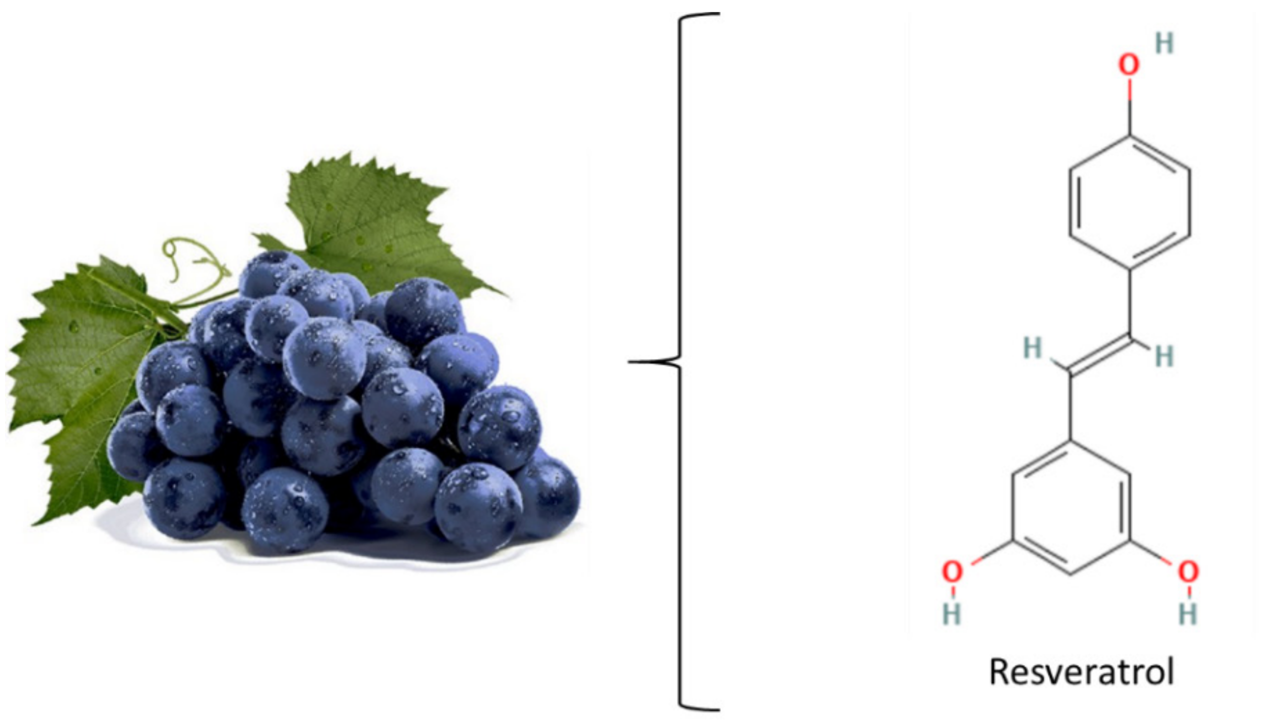
Due to its constituent biomolecules, this berry presents anti-inflammatory activity (Duarte et al., 2018), antihypertensive action (Giampieri et al., 2015), and anticancer (Folmer et al., 2014). In addition, strawberry intake promotes protection against Alzheimer's dementia (Agarwal et al., 2019). Literature showed that strawberry methanolic extract had anti-obesity action by promoting mitochondrial biogenesis, since the extract stimulated AMP-activated protein kinase, sirtuin 1 and peroxisome proliferator-activated receptor gamma 1-alpha (Forbes-Hernández et al., 2020).

3.6. *Grape*

The phytochemical diversity of grapevine includes alkaloids, terpenes, antibiotics, volatile oils, resins, cardiac glycosides, tannins, sterols, saponins and mainly phenolic compounds. Phenolic compounds are synthesized by the General Phenylpropanoid Pathway (GPP) and its downstream reactions (Rienth et al., 2021). The GPP starting point is phenylalanine, a product of the shikimate pathway that represents the fundamental link between primary and secondary metabolism in vascular plants.

The phenolic compounds present in grapes can be divided into flavonoids and non-flavonoids. The main constituent of grapes is resveratrol (Fig. 9), a non-flavonoid also known as stilbene (Ali et al., 2010). Resveratrol, which exists as a *trans* or *cis* isomer (Kiselev et al., 2017), is associated with the "French paradox" because the lower risk of cardiovascular disease in the French population was attributed to the higher intake of resveratrol through wine consumption (Renaud & De Lorgeril, 1992). Resveratrol is a compound that serves as a precursor to other stilbenoids such as piceiids, trans- and cis-resveratrol-3-O-β-D-glucopyranoside, and astringine. The oxidation of resveratrol produces oligomers called viniferins. The most important viniferines are α-, β-, γ-, δ- and ε-viniferine, consisting mainly of cyclic oligomers of resveratrol (Rienth et al., 2021).

Fig. 9. Resveratrol is the main phytochemical present in grapes.



Source: Own authorship. The molecular structure was obtained from the National Center for Biotechnology Information (https://pubchem.ncbi.nlm.nih.gov/compound/Resveratrol).

Others SM detected in grape include: *p*-coumaric acid, ellagic acid, caffeic acid, ferulic acid, coutaric acid, caftaric acid, fertaric acid, syringic acid, protocatechuic acid, gallic acid, vanillic acid, kaempferol, quercetin, myricetin, rutin, isorhamnetin, laricitrin, syringetin, catechin, epicatechin, epicatechin-3-*O*-gallate, gallocatechin, epigallocatechin, naringenin, cyanidin-3-*O*-glucoside, cyanidin-3-(6”-coumaroyl)-glucoside, cyanidin-3,5-diglucoside, peonidin-3-*O*-glucoside, peonidin-3,5-diglucoside, delfinidin-3-*O*-glucoside, delphinidin-3,5-diglucoside, delphinidin-3-(6”-acetyl)-glucoside, delphinidin-3-(6”-coumaroyl)-glucoside, petunidin-3-*O*-glucoside, petunidin-3,5-diglucoside, petunidin-3-(6”-acetyl)-glucoside, malvidin-3-*O*-glucoside, malvidin-3,5-diglucoside, linalool, geraniol, nerol, citronellol, (E)-hotrienol, α-terpineol, rose oxides and rotundone (Matarese et al., 2014; Zhang, Wang et al., 2013).

The biological effect of SM in grapes is conditioned to consumption in sufficient amounts, in raw or prepared foods, and it is also necessary that these biomolecules are bioaccessible and bioavailable (Sabra et al., 2021). Human health roles from phenolic acids include antidiabetic, anti-inflammatory, anticancer, and anti-aging activities, and radioprotective and neuroprotective actions (Kumar et al., 2018).

Resveratrol, for example, is a potent antioxidant with an important role in protecting against cardiovascular disease. The literature reports that this stilbene present in grapes affects four cardiovascular disease risk factors: platelet aggregation, hypertension, dysfunction, and hyperlipidemia (Chong et al., 2010). Use of grape seed extract (300 mg per day) and a calorie-restricted diet increases lipid levels, visceral fat index, and plasma atherosclerotic index in obese or overweight adults, thereby reducing cardiovascular risk factors (Yousefi et al., 2021). In human clinical trials, Asbaghi et al. (2021) evidenced that consumption of grape products reduced systolic and diastolic blood pressure.

4. Final considerations and future prospects

This narrative review examined the phytochemical profile of the six main small fruits and demonstrated that each of them has significant therapeutic potential when included in the daily consumption diet. All edible forms of these six berries (fresh fruit, juice, pulp and wine) are rich sources of biomolecules with health-promoting activities, particularly anthocyanins, especially in blackberries, raspberries, blueberries and strawberries.

All SM reported here perform an antioxidant action in the consumers’ body. This makes these biomolecules have high potential to fight various diseases, such as diabetes, obesity, cancer, inflammation, hypertension, neurological diseases, cardiovascular diseases, degenerative diseases and many related complications. These discoveries were possible thanks to numerous *in vitro* and *in vivo* studies, in animals and humans, from the concern of scientists, who believed that the inclusion of small fruits in diets rich in ultra-processed foods would improve the health of patients through the benefits of ingesting a complex network of phytochemicals.

Despite scientific and clinical evidence on the positive effects of eating small fruits on human health, their consumption is still low. Therefore, efforts must be made to increase the inclusion of these berries in daily diets, starting with the creation of public policies that look not only at consumers, but also at producers, scientists and industries. These initiatives will involve the totalitarian of the small fruit production chain: scientists, who develop studies to establish adequate management for the production of SM by plants and who demonstrate the benefits of these biomolecules; the producers, who envision ways to add value to the products sold and who also meet the demand of the demanding consumer market in terms of quality;

the food and pharmaceutical industries, which can originate pharmaceutical products, nutraceuticals and dietary supplements from small fruits; and consumers, who are increasingly concerned about their health and thoughtful when structuring their diets.

Credit author statement

Talison Roberto Maurer: Conceptualization, Original draft preparation, Methodology, Data curation, Writing.
Carolina Zuanazzi Tonelo: Visualization, Investigation. Bianca Oliveira Machado: Visualization, Investigation.
Thomas dos Santos Trentin: Visualization, Investigation, Data curation.
Charise Dallazem Bertol: Visualization, Investigation.
Nadia Canali Lângaro: Visualization, Investigation.
José Luís Trevizan Chiomento: Conceptualization, Original draft preparation, Methodology, Data curation, Writing, Supervision.

Declaration of competing interest

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

References

Acosta-Montoya, Ó., Vaillant, F., Cozzano, S., Mertz, C., Pérez, A. M. & Castro, M. V. (2010). Phenolic content and antioxidant capacity of tropical highland blackberry (Rubus adenotrichus Schltdl.) during three edible maturity stages. *Food Chemistry*, 119(4), 1497–1501. http://dx.doi.org/10.1016/j.foodchem.2009.09.032

Agarwal, P., Wang, Y., Holland, T., Bennett, D. & Morris, M. (2019). Strawberry consumption associated with reduced Alzheimer's dementia risk (FS05-06-19). *Current Developments in Nutrition*, 3(Suppl 1), 1–11. https://doi.org/10.1093%2Fcdn%2Fnzz052.FS05-06-19

Ali, K., Maltese, F., Choi, Y. H. & Verpoorte, R. (2010). Metabolic constituents of grapevine and grape-derived products. *Phytochemistry Reviews*, 9(3), 357–378. https://doi.org/10.1007/s11101-009-9158-0

Asbaghi, O., Naeini, F., Moodi, V., Najafi, M., Shirinbakhshmasoleh, M., Kelishadi, M. R., Hadi, A., Ghaedi, E. & Fadel, A. (2021). Effect of grape products on blood pressure: A systematic review and meta-analysis of randomized controlled trials. *International Journal of Food Properties*, 24(1), 627–645. https://doi.org/10.1080/10942912.2021.1901731

Buran, T. J., Sandhu, A. K., Li, Z., Rock, C. R., Yang, W. W. & Gu, L. (2014). Adsorption/desorption characteristics and separation of anthocyanins and polyphenols from blueberries using macroporous adsorbent resins. *Journal of Food Engineering*, 128, 167–173. http://dx.doi.org/10.1016/j.jfoodeng.2013.12.029

Burton-Freeman, B. M., Sandhu, A. K. & Edirisinghe, I. (2016). Red raspberries and their bioactive polyphenols: Cardiometabolic and neuronal health links. *Advances in Nutrition*, 7(1), 44–65. https://doi.org/10.3945/an.115.009639

Chai, Z., Herrera-Balandrano, D. D., Yu, H., Beta, T., Zeng, Q., Zhang, X., Tian, L., Niu, L. & Huang, W. (2021). A comparative analysis on the anthocyanin composition of 74 blueberry cultivars from China. *Journal of Food Composition and Analysis*, 102(4), 1–10. https://doi.org/10.1016/j.jfca.2021.104051

Chaves, V. C., Calvete, E. O. & Reginatto, F. H. (2017). Quality properties and antioxidant activity of seven strawberry (*Fragaria x ananassa* Duch.) cultivars. *Scientia Horticulturae*, 225(10), 293–298. http://dx.doi.org/10.1016/j.scienta.2017.07.013

Chen, L., Xin, X., Zhang, H. & Yuan, Q. (2013). Phytochemical properties and antioxidant capacities of commercial raspberry varieties. *Journal of Functional Foods*, 5(1), 508–515. https://doi.org/10.1016/j.jff.2012.10.009

Chiomento, J. L., De Nardi, F. S., Filippi, D., Trentin, T. S., Dornelles, A. G., Fornari, M., Nienow, A. A. & Calvete, E. O. (2021). Morpho-horticultural performance of strawberry cultivated on substrate with arbuscular mycorrhizal fungi and biochar. *Scientia Horticulturae*, 282, 1–10. https://doi.org/10.1016/j.scienta.2021.110053

Chiomento, J. L., De Nardi, F. S., Kujawa, S. C., Deggerone, Y. S., Fante, R., Kaspary, I. J., Dornelles, A. G., Huzar-Novakowiski, J. & Trentin, T. S. (2023). Multivariate contrasts of seven strawberry cultivars in soilless cultivation and greenhouse in southern Brazil. *Advanced Chemicobiology Research*, 2(1), 62–76. https://doi.org/10.37256/acbr.2120232332

Chiomento, J. L., Lima Júnior, E. P., D'Agostini, M., De Nardi, F. S., Trentin, T. S., Dornelles, A. G., Huzar-Novakowiski, J. & Calvete, E. O. (2021). Horticultural potential of nine strawberry cultivars by greenhouse production in Brazil: A view through multivariate analysis. *Scientia Horticulturae*, 279, 1–10. https://doi.org/10.1016/j.scienta.2020.109738

Chong, M. F., Macdonald, R. & Lovegrove, J. A. (2010). Fruit polyphenols and CVD risk: A review of human intervention studies. *British Journal of Nutrition*, 104(Suppl 3), 28–39. https://doi.org/10.1017/s0007114510003922

Clifford, M. N. & Scalbert, A. (2000). Ellagitannins: Nature, occurrence and dietary burden. *Journal of the Science of Food and Agriculture*, 80(7), 1118–1125. https://doi.org/10.1002/(SICI)1097-0010(20000515)80:7%3C1118::AID-JSFA570%3E3.0.CO;2-9

Correa-Betanzo, J., Padmanabhan, P., Corredig, M., Subramanian, J. & Paliyath, G. (2015). Complex formation of blueberry (Vaccinium angustifolium) anthocyanins during freeze-drying and its influence on their biological activity. *Journal of Agricultural and Food Chemistry*, 63(11), 2935–2946. https://doi.org/10.1021/acs.jafc.5b00016

Cvetković, M., Kočić, M., Dabić Zagorac, D., Ćirić, I., Natić, M., Hajder, Đ., Životić, A. & Fotirić Akšić, M. (2022). When is the right moment to pick blueberries? Variation in agronomic and chemical properties of blueberry (Vaccinium corymbosum) cultivars at different harvest times. *Metabolites*, 12(9), 1–19. https://doi.org/10.3390/metabo12090798

De Pascual-Teresa, S., Moreno, D. A. & Garcia-Viguera, C. (2010). Flavanols and anthocyanins in cardiovascular health: A review of current evidence. *International Journal of Molecular Sciences*, 11(4), 1679–1703. https://doi.org/10.3390%2Fijms11041679

Diaconeasa, Z., Florica, R., Rugină, D., Lucian, C. & Socaciu, C. (2014). HPLC/PDA–ESI/MS Identification of phenolic acids, flavonol glycosides and antioxidant potential in blueberry, blackberry, raspberries and cranberries. *Journal of Food and Nutrition Research*, 2(11), 781–785. https://doi.org/10.12691/jfnr-2-11-4

Di Lorenzo, C., Colombo, F., Biella, S., Stockley, C. & Restani, P. (2021). Polyphenols and human health: The role of bioavailability. *Nutrients*, 13(1), 1–30. https://doi.org/10.3390%2Fnu13010273

Ding, Y., Zhang, B., Zhou, K., Chen, M., Wang, M., Jia, Y., Song, Y., Li, Y. & Wen, A. (2014). Dietary ellagic acid improves oxidant-induced endothelial dysfunction and atherosclerosis: Role of Nrf2 activation. *International Journal of Cardiology*, 175(3), 508–514. https://doi.org/10.1016/j.ijcard.2014.06.045

Draelos, Z., Dahl, A., Yatskayer, M., Chen, N., Krol, Y. & Oresajo, C. (2013). Dyspigmentation, skin physiology, and a novel approach to skin lightening. *Journal of Cosmetic Dermatology*, 12(4), 247–253. https://doi.org/10.1111/jocd.12066

Duarte, L. J., Chaves, V. C., Nascimento, M. V. P. S., Calvete, E. O., Li, M., Ciraolo, E., Ghigo, A., Hirsch, E., Simões, C. M. O., Reginatto, F. H. & Dalmarco, E. M. (2018). Molecular mechanism of action of pelargonidin-3-O-glucoside, the main anthocyanin responsible for the anti-inflammatory effect of strawberry fruits. *Food Chemistry*, 247, 56–65. https://doi.org/10.1016/j.foodchem.2017.12.015

Etzbach, L., Pfeiffer, A., Weber, F. & Schieber, A. (2018). Characterization of carotenoid profiles in goldenberry (*Physalis peruviana* L.) fruits at various ripening stages and in different plant tissues by HPLC-DAD-APCI-MSn. *Food Chemistry*, 245, 508–517. https://doi.org/10.1016/j.foodchem.2017.10.120

Felgus-Lavefve, L., Howard, L., Adams, S. H. & Baum, J. I. (2022). The effects of blueberry phytochemicals on cell models of inflammation and oxidative stress. *Advances in Nutrition*, 13(4), 1279–1309. https://doi.org/10.1093/advances/nmab137

Feng, R., Bowman, L. L., Lu, Y., Leonard, S. S., Shi, X., Jiang, B. H., Castranova, V., Vallyathan, V. & Ding, M. (2004). Blackberry extracts inhibit activating protein 1 activation and cell transformation by perturbing the mitogenic signaling pathway. *Nutrition and Cancer*, 50(1), 80–89. https://doi.org/10.1207/s15327914nc5001_11

Ferreira, D. S., Rosso, V. V. & Mercadante, A. Z. (2010). Bioactive compounds of blackberry fruits (Rubus spp.) grown in Brazil. *Revista Brasileira de Fruticultura*, 32(3), 664–674. https://doi.org/10.1590/S0100-29452010005000110

Folmer, F., Basavaraju, U. & Jaspars, M. (2014). Anticancer effects of bioactive berry compounds. *Phytochemistry Reviews*, 13, 295–322. https://doi.org/10.1007/s11101-013-9319-z

Forbes-Hernández, T. Y., Cianciosi, D., Ansary, J., Mezzetti, B., Bompadre, S., Quiles, J. L., Giampieri, F. & Battino, M. (2020). Strawberry (Fragaria × ananassa cv. Romina) methanolic extract promotes browning in 3T3-L1 cells. *Food & Function*, 11(1), 297–304. https://doi.org/10.1039/C9FO02285F

Gancel, A. L., Feneuil, A., Acosta, O., Pérez, A. M. & Vaillant, F. (2011). Impact of industrial processing and storage on major polyphenols and the antioxidant capacity of tropical highland blackberry (Rubus adenotrichus). *Food Research International*, 44(7), 2243–2251. http://dx.doi.org/10.1016/j.foodres.2010.06.013

Garcia-Seco, D., Zhang, Y., Gutierrez-Mañero, F. J., Martin, C. & Ramos-Solano, B. (2015). Application of Pseudomonas fluorescens to blackberry under field conditions improves fruit quality by modifying flavonoid metabolism. *PLoS One*, 10(11), 1–23. https://doi.org/10.1371/journal.pone.0142639

Giampieri, F., Alvarez-Suarez, J. M., Mazzoni, L., Forbes-Hernandez, T. Y., Gasparrini, M., Gonzàlez-Paramàs, A. M. & Battino, M. (2014). An anthocyanin-rich strawberry extract protects against oxidative stress damage and improves mitochondrial functionality in human dermal fibroblasts exposed to an oxidizing agent. *Food & Function*, 5(8), 1939–1948. https://doi.org/10.1039/c4fo00048j

Giampieri, F., Forbes-Hernandez, T. Y., Gasparrini, M., Alvarez-Suarez, J. M., Afrin, S., Bompadre, S., Quiles, J. L., Mezzetti, B. & Battino, M. (2015). Strawberry as a health promoter: An evidence based review. *Food & Function*, 6(5), 1386–1398. https://doi.org/10.1039/c5fo00147a

Giusti, M. M. & Jing, P. (2007). Natural pigments of berries: functionality and application. In Y. Zhao, *Berry Fruit. Value-Added Products for Health Promotion* (pp. 105–146). CRC Press. https://doi.org/10.1201/9781420006148

Gowd, V., Bao, T., Wang, L., Huang, Y., Chen, S., Zheng, X., Cui, S. & Chen, W. (2018). Antioxidant and antidiabetic activity of blackberry after gastrointestinal digestion and human gut microbiota fermentation. *Food Chemistry*, 269, 618–627. https://doi.org/10.1016/j.foodchem.2018.07.020

Howard, L. R., Brownmiller, C. & Prior, R. L. (2014). Improved color and anthocyanin retention in strawberry puree by oxygen exclusion. *Journal of Berry Research*, 4(2), 107–116. https://doi.org/10.3233/JBR-140072

Isah, T. (2019). Stress and defense responses in plant secondary metabolites production. *Biological Research*, 52(39), 1–25. https://doi.org/10.1186/s40659-019-0246-3

Jamwal, K., Bhattacharya, S. & Puri, S. (2018). Plant growth regulator mediated consequences of secondary metabolites in medicinal plants. *Journal of Applied Research on Medicinal and Aromatic Plants*, 9, 26–38. https://doi.org/10.1016/j.jarmap.2017.12.003

Johnson, I. T. (2002). Glucosinolates in the human diet. Bioavailability and implications for health. *Phytochemistry Reviews*, 1, 183–188. https://doi.org/10.1023/A:1022507300374

Joshipura, K. J., Hu, F. B., Manson, J. E., Stampfer, M. J., Rimm, E. B., Speizer, F. E. & Willett, W. C. (2001). The effect of fruit and vegetable intake on risk for coronary heart disease. *Annals of Internal Medicine*, 134(12), 1106–1114. https://doi.org/10.7326/0003-4819-134-12-200106190-00010

Kähkönen, M., Kylli, P., Ollilainen, V., Salminen, J. P. & Heinonen, M. (2012). Antioxidant activity of isolated ellagitannins from red raspberries and cloudberries. *Journal of Agricultural and Food Chemistry*, 60(5), 1167–1174. https://doi.org/10.1021/jf203431g

Kalea, A. Z., Lamari, F. N., Theocharis, A. D., Cordopatis, P., Schuschke, D. A., Karamanos, N. K., Klimis-Zacas, D. J. (2006). Wild blueberry (Vaccinium angustifolium) consumption affects the composition and structure of glycosaminoglycans in Sprague-Dawley rat aorta. *Journal of Nutritional Biochemistry*, 17(2), 109–116. https://doi.org/10.1016/j.jnutbio.2005.05.015

Kalt, W., Cassidy, A., Howard, L. R., Krikorian, R., Stull, A. J., Tremblay, F. & Zamora-Ros, R. (2020). Recent research on the health benefits of blueberries and their anthocyanins. *Advances in Nutrition*, 11(2), 224–236. https://doi.org/10.1093/advances/nmz065

Kiselev, K. V., Aleynova, O. A., Grigorchuk, V. P. & Dubrovina, A. S. (2017). Stilbene accumulation and expression of stilbene biosynthesis pathway genes in wild grapevine Vitis amurensis Rupr. *Planta*, 245(1), 151–159. https://doi.org/10.1007/s00425-016-2598-z

Kist, B. B., Carvalho, C. & Beling, R. R. (2022). *Anuário Brasileiro de Horti e Fruti.* Editora Gazeta. https://www.editoragazeta.com.br/produto/anuario-brasileiro-de-horti-fruti-2022/

Knobloch, T. J., Uhrig, L. K., Pearl, D. K., Casto, B. C., Warner, B. M., Clinton, S. K., Sardo-Molmenti, C. L., Ferguson, J. M., Daly, B. T., Riedl, K., Schwartz, S. J., Vodovotz, Y., Buchta Sr, A. J., Schuller, D. E., Ozer, E., Agrawal, A. & Weghorst, C. M. (2016). Suppression of pro-inflammatory and pro-survival biomarkers in oral cancer patients consuming a black raspberry phytochemical-rich troche. *Cancer Prevention Research*, 9(2), 159–171. https://doi.org/10.1158/1940-6207.capr-15-0187

Kolniak-Ostek, J., Kucharska, A. Z., Sokół-Łętowska, A. & Fecka, I. (2015). Characterization of phenolic compounds of thorny and thornless blackberries. *Journal of Agricultural and Food Chemistry*, 63(11), 3012–3021. https://doi.org/10.1021/jf5039794

Kumar, A., Mosa, K. A., Ji, L., Kage, U., Dhokane, D., Karre, S., Madalageri, D. & Pathania, N. (2018). Metabolomics-assisted biotechnological interventions for developing plant-based functional foods and nutraceuticals. *Critical Reviews in Food Science and Nutrition*, 58(11), 1791–1807. https://doi.org/10.1080/10408398.2017.1285752

Lara, M. V., Bonghi, C., Famiani, F., Vizzotto, G., Walker, R. P. & Drincovich, M. F. (2020). Stone fruit as biofactories of phytochemicals with potential roles in human nutrition and health. *Frontiers in Plant Science*, 11, 1–21. https://doi.org/10.3389/fpls.2020.562252

Li, D., Zhang, Y., Liu, Y., Sun, R. & Xia, M. (2015). Purified anthocyanin supplementation reduces dyslipidemia, enhances antioxidant capacity, and prevents insulin resistance in diabetic patients. *Journal of Nutrition*, 145(4), 742–748. https://doi.org/10.3945/jn.114.205674

Liu, R. H. (2013). Health-promoting components of fruits and vegetables in the diet. *Advances in Nutrition*, 4(3), 384S–392S. https://doi.org/10.3945/an.112.003517

Liu, R. H. (2004). Potential synergy of phytochemicals in cancer prevention: Mechanism of action. *The Journal of Nutrition*, 134(12 Suppl), 3479S–3485S. https://doi.org/10.1093/jn/134.12.3479s

Liu, Y., Liu, M., Li, B., Zhao, J.-L., Zhang, C.-P., Lin, L.-Q., Chen, H.-S., Zhang, J.-S., Jin, J.-C., Wang, L., Li, L.-J. & Liu, J.-R. (2010). Fresh raspberry phytochemical extract inhibits hepatic lesion in a Wistar rat model. *Nutrition & Metabolism*, 7(84), 1–8. https://doi.org/10.1186/1743-7075-7-84

Maksimović, J. J. D., Milivojević, J. M., Poledica, M. M., Nikolić, M. D. & Maksimović, V. M. (2013). Profiling antioxidant activity of two primocane fruiting red raspberry cultivars (Autumn bliss Polka). *Journal of Food Composition and Analysis*, 31(2), 173–179. http://dx.doi.org/10.1016/j.jfca.2013.05.008

Matarese, F., Cuzzola, A., Scalabrelli, G. & D'Onofrio, C. (2014). Expression of terpene synthase genes associated with the formation of volatiles in different organs of Vitis vinifera. *Phytochemistry*, 105, 12–24. https://doi.org/10.1016/j.phytochem.2014.06.007

Mazova, N., Popova, V. & Stoyanova, A. (2020). Phytochemical composition and biological activity of Physalis spp.: A mini-review. *Food Science and Applied Biotechnology*, 3(1), 56–70. http://dx.doi.org/10.30721/fsab2020.v3.i1.80

Monjotin, N., Amiot, M. J., Fleurentin, J., Morel, J. M. & Raynal, S. (2022). Clinical evidence of the benefits of phytonutrients in human healthcare. *Nutrients*, 14, 1–54. https://doi.org/10.3390%2Fnu14091712

Muñoz, P., Parra, F., Simirgiotis, M. J., Sepúlveda-Chavera, G. F. & Parra, C. (2021). Chemical characterization, nutritional and bioactive properties of Physalis peruviana fruit from high areas of the Atacama Desert. *Foods*, 10(11), 1–13. https://doi.org/10.3390/foods10112699

Olivares-Tenorio, M. L., Verkerk, R., Van Boekel, M. A. J. S. & Dekker, M. (2017). Thermal stability of phytochemicals, HMF and antioxidant activity in cape gooseberry (*Physalis peruviana* L.). *Journal of Functional Foods*, 32, 46–57. https://doi.org/10.1016/j.jff.2017.02.021

Pant, P., Pandey, S. & Dall'Acqua, S. (2021). The influence of environmental conditions on secondary metabolites in medicinal plants: A literature review. *Chemistry & Biodiversity*, 18(11), 1–14. https://doi.org/10.1002/cbdv.202100345

Ramakrishna, A. & Ravishankar, G. A. (2011). Influence of abiotic stress signals on secondary metabolites in plants. *Plant Signaling & Behavior*, 6(11), 1720–1731. https://doi.org/10.4161%2Fpsb.6.11.17613

Rao, A. V. & Snyder, D. M. (2010). Raspberries and human health: A review. *Journal of Agricultural and Food Chemistry*, 58(7), 3871–3883. https://doi.org/10.1021/jf903484g

Reis, J. F., Monteiro, V. V. S., Souza Gomes, R., Carmo, M. M., Costa, G. V., Ribera, P. C. & Monteiro, M. C. (2016). Action mechanism and cardiovascular effect of anthocyanins: A systematic review of animal and human studies. *Journal of Translational Medicine*, 14(1), 1–16. https://doi.org/10.1186/s12967-016-1076-5

Renaud, S. & De Lorgeril, M. (1992). Wine, alcohol, platelets, and the French paradox for coronary heart disease. *Lancet*, 339(8808), 1523–1526. https://doi.org/10.1016/0140-6736(92)91277-f

Rienth, M., Vigneron, N., Darriet, P., Sweetman, C., Burbidge, C., Bonghi, C., Walker, R. P., Famiani, F. & Castellarin, S. D. (2021). Grape berry secondary metabolites and their modulation by abiotic factors in a climate change scenario: A review. *Frontiers in Plant Science*, 12, 1–26. https://doi.org/10.3389/fpls.2021.643258

Roth, S., Spalinger, M. R., Gottier, C., Biedermann, L., Zeitz, J., Lang, S., Weber, A., Rogler, G. & Scharl, M. (2016). Bilberry-derived anthocyanins modulate cytokine expression in the intestine of patients with ulcerative colitis. *PLoS One*, 11(5), 1–17. https://doi.org/10.1371/journal.pone.0154817

Sabra, A., Netticadan, T. & Wijekoon, C. (2021). Grape bioactive molecules, and the potential health benefits in reducing the risk of heart diseases. *Food Chemistry*, 12, 1–13. https://doi.org/10.1016/j.fochx.2021.100149

Sangiovanni, E., Vrhovsek, U., Rossoni, G., Colombo, E., Brunelli, C., Brembati, L., Trivulzio, S., Gasperotti, M., Mattivi, F., Bosisio, E. & Dell'Agli, M. (2013). Ellagitannins from Rubus berries for the control of gastric inflammation: in vitro and in vivo studies. *PLoS One*, 8(8), 1–12. https://doi.org/10.1371/journal.pone.0071762

Skrovankova, S., Sumczynski, D., Mlcek, J., Jurikova, T. & Sochor, J. (2015). Bioactive compounds and antioxidant activity in different types of berries. *International Journal of Molecular Sciences*, 16(10), 24673–24706. https://doi.org/10.3390/ijms161024673

Song, J., Li, Y., Ge, J., Duan, Y., Sze, S. C. W., Tong, Y., Shaw, P. C., Ng, T. B., Tsui, K. C., Zhuo, Y. & Zhang, K. Y. (2010). Protective effect of bilberry (Vaccinium myrtillus L.) extracts on cultured human corneal limbal epithelial cells (HCLEC). *Phytotherapy Research*, 24(4), 520–524. https://doi.org/10.1002/ptr.2974

Soppelsa, S., Kelderer, M., Casera, C., Bassi, M., Robatscher, P., Matteazzi, A. & Andreotti, C. (2019). Foliar applications of biostimulants promote growth, yield and fruit quality of strawberry plants grown under nutrient limitation. *Agronomy*, 9(9), 1–22. https://doi.org/10.3390/agronomy9090483

Torre, L. C. & Barritt, B. H. (1977). Quantitative evaluation of Rubus fruit anthocyanin pigments. *Journal of Food Science*, 42(2), 488–490. https://doi.org/10.1111/j.1365-2621.1977.tb01528.x

Torres-Urrutia, C., Guzman, L., Schmeda-Hirschmann, G., Moore-Carrasco, R., Alarcon, M., Astudillo, L., Gutierrez, M., Carrasco, G., Yuri, J. A., Aranda, E. & Palomo, I. (2011). Antiplatelet, anticoagulant, and fibrinolytic activity in vitro of extracts from selected fruits and vegetables. *Blood Coagulation & Fibrinolysis*, 22(3), 197–205. https://doi.org/10.1097/mbc.0b013e328343f7da

Tuteja, N. & Mahajan, S. (2007). Calcium signaling network in plants: An overview. *Plant Signaling & Behavior*, 2(2), 79–85. https://doi.org/10.4161%2Fpsb.2.2.4176

Van Breda, S. G. J., Briedé, J. J. & De Kok, T. (2018). Improved preventive effects of combined bioactive compounds present in different blueberry varieties as compared to single phytochemicals. *Nutrients*, 11(1), 1–14. https://doi.org/10.3390/nu11010061

Wang, S., Wang, B., Dong, K., Li, J., Li, Y. & Sun, H. (2022). Identification and quantification of anthocyanins of 62 blueberry cultivars via UPLC-MS. *Biotechnology & Biotechnological Equipment*, 36(1), 587–597. https://doi.org/10.1080/13102818.2022.2090857

Yamika, W. S. D., Aini, N. & Waluyo, B. (2019). *Physalis peruviana* L.: Growth, yield and phytochemical content - A review. *Agricultural Reviews*, 4(4), 147–152. http://dx.doi.org/10.18805/ag.R-130

Yoshimura, M., Watanabe, Y., Kasai, K., Yamakoshi, J. & Koga, T. (2005). Inhibitory effect of an ellagic acid-rich pomegranate extract on tyrosinase activity and ultraviolet-induced pigmentation. *Bioscience, Biotechnology and Biochemistry*, 69(12), 2368–2373. https://doi.org/10.1271/bbb.69.2368

Yousefi, R., Parandoosh, M., Khorsandi, H., Hosseinzadeh, N., Tonekaboni, M. M., Saidpour, A., Babaei, H. & Ghorbani, A. (2021). Grape seed extract supplementation along with a restricted-Calorie diet improves cardiovascular risk factors in obese or overweight adult individuals: A randomized, placebo-Controlled trial. *Phytotherapy Research*, 35(2), 987–995. https://doi.org/10.1002/ptr.6859

Zhang, L., Wang, Z. & Zhang, W. (2013). Determination of caftaric acid, p-coutaric acid and fertaric acid in grape juice, peel and seeds by ultra-high performance liquid chromatography-tandem quadrupole mass spectrometry. *Chinese Journal of Chromatography*, 31(2), 122–126. https://doi.org/10.3724/sp.j.1123.2012.09047

Zhang, Y.-J., Deng, G., Ru, X., Wu, S., Li, S. & Li, H. (2013). Chemical components and bioactivities of Cape gooseberry (*Physalis peruviana*). *International Journal of Food Nutrition and Safety*, 3(1), 15–24. https://modernscientificpress.com/journals/ViewArticle.aspx?6ZIT7oAL6Lqarm6Ljqm1AEElk+hj9A+fv9GWpU/xhwwRe+2q2RWNomBD9aIj2kYX

Talison Roberto Maurer. University of Passo Fundo, Passo Fundo, RS, Brazil.

Carolina Zuanazzi Tonelo. University of Passo Fundo, Passo Fundo, RS, Brazil.

Bianca Oliveira Machado. University of Passo Fundo, Passo Fundo, RS, Brazil.

Thomas dos Santos Trentin. University of São Paulo, Piracicaba, SP, Brazil

Charise Dallazem Bertol. University of Passo Fundo, Passo Fundo, RS, Brazil.

Nadia Canali Lângaroa. University of Passo Fundo, Passo Fundo, RS, Brazil.

José Luís Trevizan Chiomento. University of Passo Fundo, Passo Fundo, RS, Brazil.