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Phytochemical profiling of secondary metabolites across botanical parts of underutilized berry species: antioxidant properties and climate-resilient value chains

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Underutilized berry germplasm represents an important resource for diversifying food systems, improving nutritional security, and supporting climate-resilient horticulture. Berry fruits are rich sources of bioactive compounds, including polyphenols, anthocyanins, flavonols, phenolic acids, carotenoids, polysaccharides, vitamins, and minerals, which contribute to their antioxidant and health-promoting properties. The present review examines twelve underexploited berry taxa such as *Ribes*, *Aronia*, *Hippophae*, *Lonicera*, *Sambucus*, *Morus*, *Vaccinium vitis-idaea*, *Lycium*, *Cornus*, *Physalis*, and *Amelanchier*, with emphasis on their nutritional composition, antioxidant potential, ecological adaptability, and commercialization prospects. A targeted literature survey, supported by agricultural database queries, was used to evaluate research intensity, dominant classes of bioactive compounds, and species-specific strengths, such as the high polyphenol content of *Aronia* and *Vaccinium vitis-idaea*, the valorization potential of seed fractions and polysaccharides in *Lycium*, and the soil-stabilizing, low-input suitability of *Hippophae*. In addition, processing pathways and emerging market applications, including fresh consumption, juices, extracts, oils, and nutraceutical products are discussed alongside major constraints limiting large-scale adoption. Recent pharmacological and clinical evidence supporting the functional potential of these berries is also summarized. Overall, this review highlights that underutilized berry species possess significant nutritional, ecological, and economic potential; however, further efforts in agronomic optimization, standardized processing, regulatory alignment, and clinical validation are required to facilitate their broader integration into sustainable food and health systems.

KEYWORDS

bioactive phytochemicals, climate-resilient horticulture, functional food applications, nutritional and antioxidant potential, underutilized berry crops

Botanical part	Key-compounds	Health benefit	Utilization
	• Polyphenols • Carotenoids • Terpenoids • Fatty acids • Organic acids • Phytosterols • Tocopherols	• Antioxidant activity • Lipid peroxidation inhibition • Improvement hepatic lipid metabolism • Reduction plasma lipid peroxidation (...)	• Fresh fruit • Dried fruit • Jam • Beverage • Medicine 
	• Alkaloids • Polyphenols • Carotenoids • Terpenoids (Withanolides) • Fatty acids	• Lipid peroxidation inhibition • Anti-diabetic activity, with regeneration of pancreatic β-cells (...)	• Beverage, infusion (...) 
	• Lipids • Glycosides • Phytosterols • Polysaccharides • Tocopherols	• Anti-diabetic activity, with regeneration of pancreatic β-cells • Efficient stigmasterol extraction • Nutraceutical potential	• Oil 
	• Alkaloids • Polyphenols • Terpenoids (Withanolides)	• Antiviral activity of root bark-derived flavonoids	• Traditional medicine 

GRAPHICAL ABSTRACT

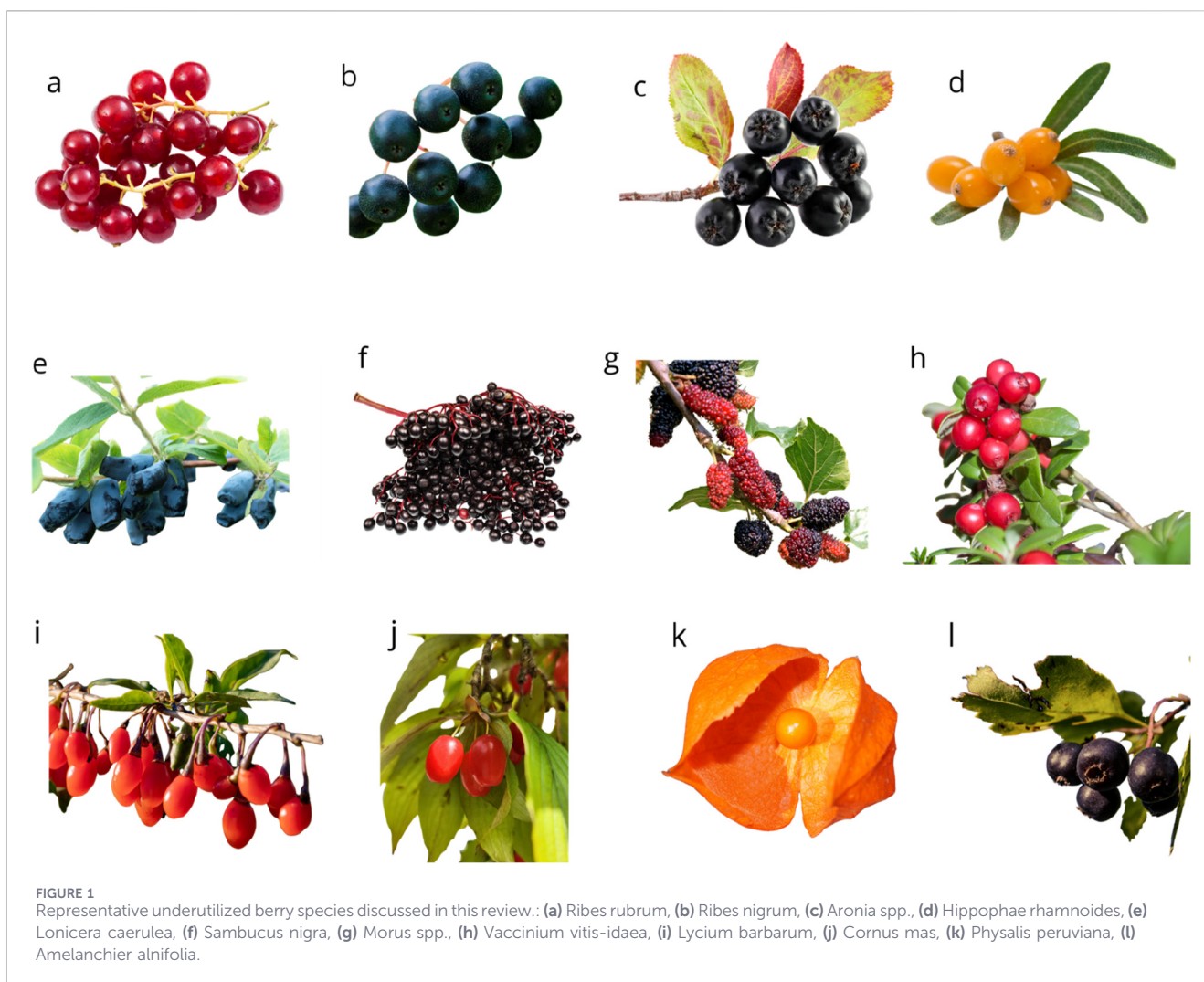
1 Introduction

In recent decades, increasing anthropogenic perturbation of the atmosphere has imposed substantial challenges on global agricultural systems, primarily through prolonged temperature extremes, irregular rainfall patterns, and increased climatic variability (Adamo et al., 2021; Spiridonov et al., 2025; Qiu et al., 2024). The conventional farming has shown limited resilience to these climate-related stressors, resulting in physiological disorders and consequent reductions in productivity and yield stability (Roy et al., 2021; Karagatiya et al., 2023; Indurthi et al., 2024). Therefore, contemporary breeding strategies increasingly emphasize the selection of genotypes capable of adapting to or overcoming adverse environmental constraints (Varshney et al., 2021; Xiong et al., 2022). In this context, the conservation and utilization of diverse fruit plant species are essential not only for safeguarding food heritage but also for enhancing agricultural resilience under changing climatic conditions.

Berry fruits are widely considered as essential elements for a healthy diet due to their high content of bioactive compounds,

including vitamins, minerals, dietary fibre, polyphenols, anthocyanins, carotenoids and other phytochemicals (Djordjević, 2023). These compounds have been extensively documented for their antioxidant, anti-inflammatory, antidiabetic, anticancer and overall health-promoting properties. Nevertheless, research and commercial cultivation efforts have largely focused on a limited number of well-known berry species, leaving a substantial pool of underutilized fruit germplasm insufficiently explored despite its high potential (Sofi et al., 2025).

Underutilized berry species, often represented by indigenous or locally adapted genotypes, typically grow in marginal environments and exhibit inherent tolerance to multiple abiotic stresses such as drought and salinity, making them particularly promising candidates for the development of climate-resilient agricultural systems (Csorba et al., 2020; Ritika et al., 2024). Beyond their ecological adaptability, many of these so-called “minors” or “neglected” berries display exceptional nutritional profiles, frequently exceeding those of commercially cultivated counterparts in specific phytochemical concentrations (Wan et al., 2025).

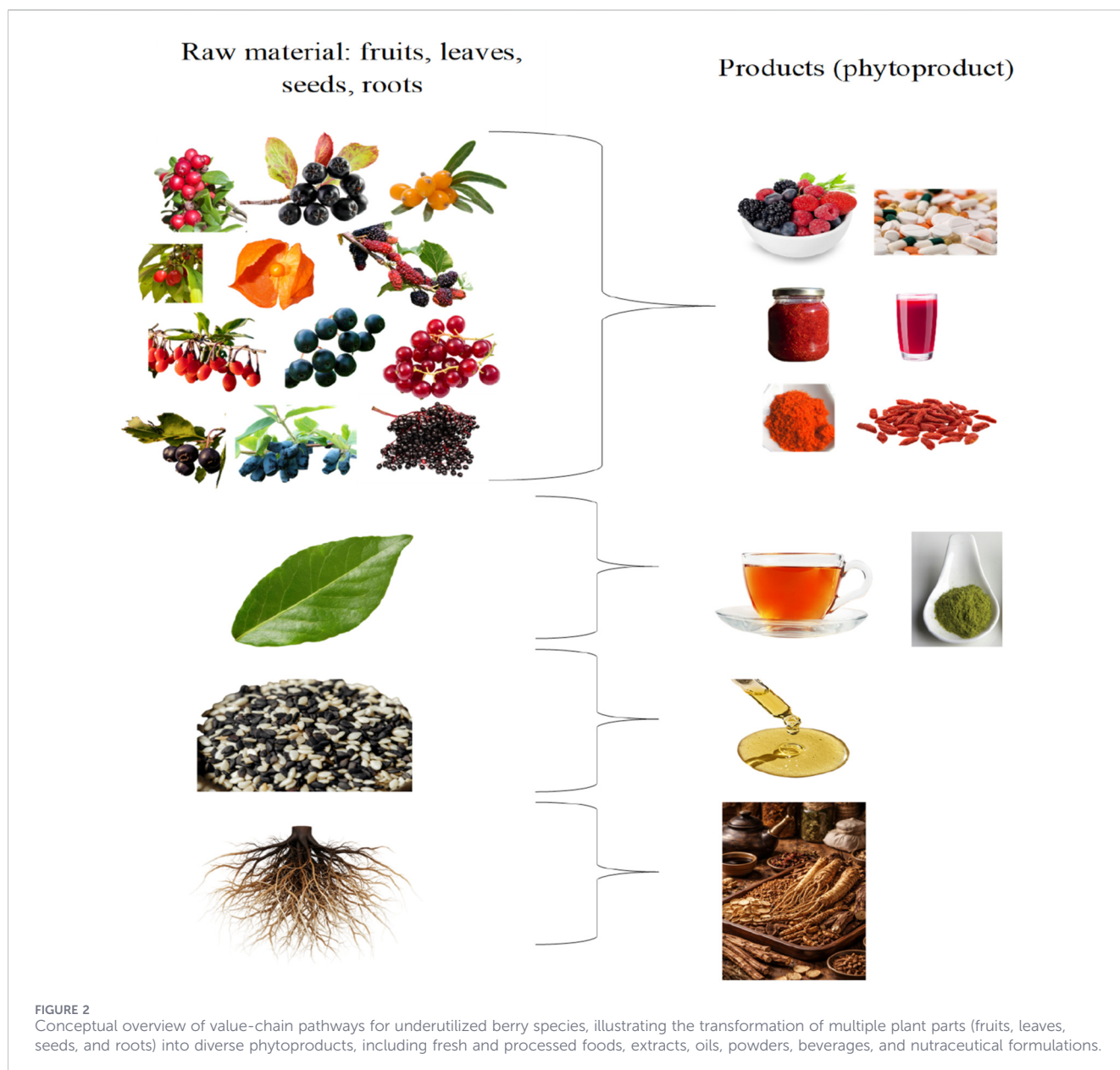


Among underutilized berry crops, *Ribes* spp. represent the most widely cultivated group. The most commonly cultivated species, *Ribes rubrum* (red currant) and *Ribes nigrum* (black currant), are characterized by low caloric value and high contents of vitamin C, B-group vitamins, minerals, dietary fibre and phenolic compounds (Kidoń and Narasimhan, 2022; Kierońska et al., 2024). *Aronia* spp (chokeberry), native to North America and eastern Canada, are particularly renowned for their exceptionally high anthocyanin content and associated antioxidant capacity (Jelska et al., 2024; Sarıkaya et al., 2025; Kaczmarczyk et al., 2025; Duman et al., 2025). *Hippophae rhamnoides* (sea buckthorn), a highly resilient species native to cold regions of Eurasia, is a rich source of vitamins (C, E, and K), carotenoids, and fatty acids and is capable of thriving under saline and nutrient-poor soil conditions (He et al., 2023). Similarly, *Lonicera caerulea* (honeyberry), a species adapted to cold and high-latitude environments and traditionally described as having “homology of medicine and food,” contains unique phenolic compounds, including anthocyanins such as cyanidin-3-glucoside, which contribute to its health-promoting properties (Cheng et al., 2022; Guo et al., 2023). *Sambucus nigra* (elderberry) has been extensively studied for its antioxidant, antimicrobial, anti-inflammatory, anticancer, immunomodulatory

and antidiabetic activities (Liu et al., 2022; Uhl and Mitchell, 2024). Other promising underutilized berry species include *Morus* spp (mulberry), which exhibit a wide range of beneficial effects on human health (Martins et al., 2023; Baciú et al., 2023), *Vaccinium vitis-idaea* (lingonberry), known for its high phenolic content (Pärnänen et al., 2021; Urbonavičienė et al., 2023) and *Lycium barbarum* (goji berry), which has gained attention for its functional properties as a food ingredient with health-promoting potential (Yu et al., 2023; Vidović et al., 2022).

In addition, *Cornus mas* (Cornelian cherry) has been reported to exert beneficial effects on blood parameters through its anthocyanin content (Szot et al., 2024; Sevindik et al., 2024), while *Physalis peruviana* (cape gooseberry) has demonstrated potential in regulating blood glucose levels (Ndahura et al., 2025; Gruiescu et al., 2022). *Amelanchier alnifolia* (Saskatoon berry) is another underutilized species rich in phytochemicals, including polyphenols, polysaccharides, and volatile compounds, contributing to its growing interest as a functional fruit crop (Wang S. L. et al., 2024; Li et al., 2025).

Despite their recognized nutritional and functional value, many underutilized berry species remain largely unknown outside their regions of origin and are often harvested from wild populations



rather than cultivated systems (Salo et al., 2021). Historically, several of these berries have been used by Indigenous communities for centuries as both food and medicinal resources, underscoring their long-standing ethnobotanical significance (Migicovsky et al., 2022). The present review aims to synthesize existing knowledge on selected underutilized berry species, with particular emphasis on their nutritional and antioxidant potential, ecological adaptability, and prospects for integration into sustainable food production systems (Figures 1, 2).

2 Literature search strategy and data extraction

To ensure a structured and transparent synthesis of available evidence, a targeted but systematic literature search strategy was

adopted. The review focused on berry species considered underutilized or marginal in global production systems, defined as taxa not explicitly represented as major commodities in international production statistics.

2.1 Identification of underutilized berry species

Berry crops with well-established global production and extensive commercialization (e.g., strawberry, raspberry, blueberry, cranberry, and gooseberry) were first identified using the FAOSTAT database and excluded from further consideration. Species absent or weakly represented in FAOSTAT, but supported by a substantial body of peer-reviewed scientific literature, were classified as underutilized and selected for detailed evaluation. Based on these criteria, twelve berry taxa were included in the present review.

2.2 Literature search strategy

Scientific publications were retrieved primarily from the Scopus database, chosen for its comprehensive coverage of agricultural, food science, biochemical, and biomedical literature. Searches were conducted within article titles, abstracts, and keywords using genus- and species-specific search strings combined with botanical part-related terms. The following keyword combinations were systematically applied for each selected species.

- “Genus OR species”
- “(Genus OR species) AND (fruit* OR berry*)”
- “(Genus OR species) AND seed*”
- “(Genus OR species) AND leaves*”
- “(Genus OR species) AND root*”

The literature search covered records from the earliest indexed documents available in Scopus up to October 2025. Only peer-reviewed journal articles published in English were considered.

2.3 Inclusion and exclusion criteria

2.3.1 Studies were included if they:

- Reported qualitative or quantitative data on nutritional composition, secondary metabolites, or bioactive compounds
- Investigated agronomic traits, abiotic stress tolerance, or cultivation characteristics
- Evaluated biological, pharmacological, or functional food-related effects using *invitro*, *invivo*, or human intervention models
- Addressed processing, valorisation, or postharvest utilization of berry fruits or other botanical parts

2.3.2 Studies were excluded if they:

- Focused exclusively on major commercial berry crops
- Lacked primary experimental or analytical data (e.g., opinion pieces without supporting evidence)
- Reported insufficient methodological detail to support interpretation

2.4 Data extraction and synthesis

From each eligible publication, data were extracted on berry species, botanical part studied, major classes of bioactive compounds, representative metabolites, experimental model, and reported biological or functional effects. Extracted information was systematically organized into comparative tables summarizing research intensity, phytochemical diversity, biological relevance, and commercialization potential across species.

Rather than performing a quantitative meta-analysis, findings were synthesized qualitatively to identify recurring trends, dominant bioactive classes, underexplored botanical parts, and gaps in current knowledge. This approach enabled cross-species comparison while accommodating methodological heterogeneity among studies, which is common in phytochemical and functional food research.

3 Description of underutilized berries

3.1 *Ribes* spp.

Ribes spp., comprising red currant (*Ribes rubrum*) and black currant (*Ribes nigrum*), are hardy deciduous shrubs native to the temperate regions of Europe, Asia, and North America (Zdunić et al., 2016). They typically grow in cool, moist environments with well-drained soils and the cultivation is spread across Central and Eastern Europe, with smaller production pockets in the United Kingdom and New Zealand. The shrubs are compact, woody perennials usually ranging from 0.6 to 1.8 m in height, producing clusters of small berries borne on slender racemes (Yandovka and Barabanov, 2021). Red currants produce bright, translucent red fruits with mild acidity, while black currants bear deep purple-black berries with a more intense aroma and tartness. Despite their long history in European horticulture, the commercial importance of *Ribes* species remains limited in many regions. Several factors contribute to their underutilization, including low consumer familiarity, the naturally tart and musky flavour of blackcurrants, and historical restrictions on their cultivation in North America due to their role as an alternate host of white pine blister rust (Zdunić et al., 2016). However, *Ribes* species possess strong potential for renewed commercialization. *Ribes* crops are adaptable to a wide range of sites and are relatively easy to grow. Labour needed to grow currants is about the same as for blueberries (*Vaccinium* spp.) and less than for many other berry crops. Since *Ribes* fruits hang well on the bushes without over-ripening, the harvest window is much longer and provides more flexibility than strawberries (*Fragaria × ananassa* Duch.), raspberries or blackberries (*Rubus* spp.). Currant fruits are flavourful and suitable for a range of uses. Red Currants are rich sources of primary metabolites, such as sugars and organic acids responsible for fruit taste. The most abundant group of secondary metabolites is polyphenols, with three predominant classes: flavonoids, tannins, and phenolic acids (Milivojević et al., 2012). Among flavonoids, the most dominant are anthocyanins (cyanidin and delphinidin-3-O-glucoside), flavonols (quercetin, kaempferol), and flavanols (catechin, epicatechin) (Djordjević et al., 2010; Mattila et al., 2016). Cyanidin-3-rutinoside, delphinidin-3-rutinoside, delphinidin-3-glucoside, and cyanidin-3-glucoside are dominant anthocyanins in black currants (Allai et al., 2020). These metabolites contribute to their high antioxidant capacity, making them attractive for functional foods, nutraceuticals, and value-added processing industries. Their adaptability to cool climates, low-input requirements and suitability for juice, concentrate, jam and extract manufacturing further strengthen their potential for expanded commercial production (Strik, 2007; Brennan et al., 2014).

3.2 *Aronia* spp.

Aronia, commonly known as chokeberry, is a hardy perennial shrub native to eastern North America and well adapted to a wide range of temperate environments worldwide. The main cultivated species include *Aronia melanocarpa* (black chokeberry), *Aronia arbutifolia* (red chokeberry), and *Aronia prunifolia* (purple chokeberry). Black chokeberry is the most widely grown due to its high pigment content and strong functional food value (Duman

et al., 2025). The shrubs typically reach 1–3 m in height, producing clusters of small, dark purple to black berries with a characteristically astringent flavour. Aronia naturally grows in moist woodlands, wetlands, and forest margins but can adapt to diverse soil types and climatic conditions, making it increasingly suitable for diversified berry cultivation (Oğuz et al., 2023). Aronia fruits are among the richest natural sources of polyphenols and anthocyanins reported in any berry crop. They contain abundant cyanidin-based anthocyanins, proanthocyanidins, phenolic acids, and flavonols, contributing to exceptionally high antioxidant capacity and demonstrated anti-inflammatory, cardioprotective, and metabolic health benefits (Taheri et al., 2013). Fresh fruits typically have an astringent and bitter taste, which has historically limited fresh consumption but they have gained significant popularity in recent years as one of the most extensively researched berry species for dietary supplements. Aronia berries are renowned for their rich content of health-promoting bioactive compounds, including polyphenols, vitamins, and minerals (Ochmian et al., 2012; Gralec et al., 2019). Due to their abundance of secondary metabolites contributing to overall health and wellbeing, *A. melanocarpa* berries have earned the title of “superberry” (Juranović Cindrić et al., 2017; Pop et al., 2022). These berries perform exceptionally well in processed products such as juices, concentrates, jams, syrups, teas, extracts, and nutraceutical powders, making them highly suitable for value-added markets. In addition to its nutritional value, Aronia is highly tolerant of diverse growing conditions. The shrubs can be cultivated on nutrient-poor or marginal soils (Bussi eres et al., 2008), withstand both dry and excessively moist environments, and tolerate very low winter temperatures. They also show natural resistance to most common plant diseases, pathogens and pests, resulting in a low-maintenance crop (Ro ca et al., 2019). Because of these traits, Aronia is increasingly used for rehabilitating degraded or abandoned lands, where few other berry species can survive.

3.3 Hippophae rhamnoides

Sea buckthorn (*Hippophae rhamnoides* L.) is a hardy deciduous shrub belonging to the Elaeagnaceae family and native to the cold-temperate regions of Europe and Asia. The name “Hippophae,” derived from the Greek words for “horse” (hippos) and “shining” (phaos), originates from the historical practice of feeding its leaves to horses to enhance their strength and coat gloss. The plant typically grows around 2 m tall, producing narrow silver-green leaves, numerous greenish-yellow flowers, and bright orange, ellipsoid berries (He et al., 2023). Well adapted to a broad range of agroecological environments, sea buckthorn thrives in deep, well-drained soils with pH 5.5–8.3 and can tolerate extreme temperatures ranging from severe winter cold to heat conditions of 40 °C–43 °C, enabling its cultivation in temperate, tropical, and subtropical regions (Khan et al., 2010). The species is exceptionally resilient, showing strong tolerance to drought, salinity, alkalinity, and nutrient-poor soils. Its extensive root system contains nitrogen-fixing nodules, making the species valuable for soil stabilization, land rehabilitation, and ecological restoration in degraded or erosion-prone areas (Yang and Kallio, 2002). The berries are the most economically important part of the plant and are traditionally used in Tibetan and Ayurvedic medicine. They are rich in

bioactive compounds, including high levels of vitamin C, vitamin E, carotenoids, flavonoids, sterols, organic acids, and a unique blend of saturated and unsaturated fatty acids—particularly omega-7—contributing to strong antioxidant, anti-inflammatory, dermatoprotective, and cardiometabolic benefits (Kubczak et al., 2022). These combined nutritional and ecological attributes have substantially increased interest in sea buckthorn cultivation, making it an attractive option for developing value-added products such as juices, concentrates, oils, nutraceutical capsules, and functional beverages, especially in regions seeking resilient and high-value berry crops.

3.4 Lonicera caerulea

Lonicera caerulea L., commonly known as honeyberry or haskap, is a hardy deciduous shrub native to the cool temperate forests of Europe, North Asia, and North America. The shrubs typically grow 1.5–2.0 m tall and bear pale yellow, melliferous flowers with a delicate aroma (Grob elna et al., 2019). Traditionally regarded by the Ainu people as an “elixir of life,” the fruit has been historically recognized for its nutritional and medicinal qualities. Honeyberry shrubs thrive in cold climates, tolerating winter temperatures as low as –40 °C (Senica et al., 2018) and are appreciated for its exceptionally early ripening, often 2 weeks before strawberries and for its notable hardiness, minimal soil requirements and natural resistance to pests and diseases (Szot and Wieniarska, 2012). The berries are elongated, dark purple and wax-coated, with flavours ranging from tart to mildly sweet depending on the cultivar (Auzanneau et al., 2018). Cultivation has expanded across Japan, China, Russia, Central and Eastern Europe, Canada, and the United States, driven by increasing demand for cold-tolerant berry crops. In the developed countries, rising lifestyle-related diseases and population ageing have increased the demand for antioxidant-rich fruits, especially those high in polyphenols (Bieniek et al., 2021). Nutritionally, honeyberries contain very high levels of vitamin C, often exceeding those of oranges, red currants, and raspberries and significant amounts of polyphenols, particularly cyanidin-3-O-glucoside, which represents up to 80%–90% of all anthocyanins and contributes to their strong antioxidant capacity (Jurikova et al., 2012; Guo et al., 2023). Their moderate sugar levels, balanced organic acid profile, and rich antioxidant composition make honeyberries suitable for a wide range of functional foods and nutraceutical products, while their extreme cold tolerance, early fruiting, and low-input requirements further position them as a highly promising crop for diversifying berry production and developing value-added health products.

3.5 Sambucus nigra

Sambucus nigra L., commonly known as black elderberry, and a member of the Adoxaceae family, is a widespread perennial deciduous shrub or small tree native to Europe, North America, and Western Asia, typically reaching up to 10 m in height and producing clusters of small white flowers followed by dark purple-black berries (Uhl and Mitchell, 2024). The plant grows as a multi-stemmed shrub that regenerates new canes each year, allowing it to form a dense, bush-like structure well suited to both wild and cultivated environments. While *S. nigra* is the principal cultivated

species, related subspecies exhibit natural variation in flower and fruit morphology and have contributed to the development of commercial cultivars. Elderberry thrives in sunny, moist, nutrient-rich soils but can tolerate a broad pH range and diverse growing conditions (Byers et al., 2012). The berries are rich in anthocyanins, flavonols, phenolic acids, and vitamins, giving them strong antioxidant properties and making them valuable as natural colourants and functional food ingredients. Dominant cyanidin-based pigments produce deep purple and red hues, offering opportunities for natural pigment extraction. Numerous studies highlight elderberry's high antioxidant capacity and bioactive profile, supporting its use in juices, syrups, extracts, and nutraceutical formulations (Bartak et al., 2020; Ferreira et al., 2022a; Boroduške et al., 2022). Although adequate processing is required to eliminate naturally occurring cyanogenic glycosides (Avena et al., 2024), elderberry remains a nutritionally dense and commercially relevant crop, and its adaptability, pigmentation potential, and high polyphenol content position *Sambucus nigra* as a promising species for expanded cultivation and value-added production chains.

3.6 *Morus* spp.

The genus *Morus*, comprising economically important species such as *M. alba* (white mulberry), *M. nigra* (black mulberry), and *M. rubra* (red mulberry), includes fast-growing perennial deciduous trees native to Asia but now widely naturalized across tropical, subtropical, and temperate regions of Europe, North America, South America, and Africa (Dhiman et al., 2020). Mulberry trees can reach 10–15 m in height and are highly adaptable, thriving in diverse soils and climatic conditions, including marginal lands with limited water availability. Roots are initially fleshy, brittle, and fragile; however, with age, strong lateral roots develop, conferring resistance to wind (Oğuz et al., 2023). The fruits are sweet, dark purple to black multiple berries rich in anthocyanins, flavonoids, phenolic acids, vitamins, minerals, and essential amino acids, giving them strong antioxidant, anti-inflammatory, antidiabetic and cardioprotective potential. Their favourable flavour profile, high pigment content, and nutritional value make them suitable for a wide range of processed products, including juices, syrups, molasses, jams, wines, fruit leather, and traditional health beverages. Mulberry juice, in particular, has gained strong commercial interest in China, Japan, and Korea; fresh juice can retain acceptable quality for up to 3 months under refrigeration without added preservatives, while bottled products remain stable for up to 12 months at room temperature, underscoring its suitability for value-added processing and broader market distribution (Yadav et al., 2014; Oğuz et al., 2023). Together with their low cultivation requirements, broad adaptability and growing consumer demand for antioxidant-rich fruits, mulberry represents an increasingly attractive crop for expanding berry-based functional food chains and developing diversified horticultural systems.

3.7 *Vaccinium vitis-idaea*

Vaccinium vitis-idaea L., commonly known as lingonberry, is a hardy evergreen shrub native to the boreal forests of Scandinavia, Central and Eastern Europe, Russia, and North America, where it

grows naturally in acidic, nutrient-poor soils (Mane et al., 2011). It is a slow-growing, bushy shrub that can reach a height of 10–40 cm. The berries were traditionally harvested from the wild environments, as commercial cultivation and breeding remain limited compared to other *Vaccinium* species (Gustavsson, 2001). Lingonberries produce small, bright red fruits widely consumed in the form of jams, juices, syrups, and compotes. Although closely related to cranberries (*Vaccinium oxycoccus*), lingonberries have historically been less known and commercially underexploited; however, interest in the species has increased due to their high phenolic content and strong health-promoting properties (Kowalska, 2021). Nutritionally, lingonberries are exceptionally rich in polyphenols including cyanidin-based anthocyanins, proanthocyanidins, flavonols, and phenolic acids alongside vitamins A, C, and E and essential minerals. Wild populations often exhibit higher phenolic concentrations due to environmental stress-induced metabolite accumulation. Extensive research demonstrates that lingonberry bioactive compounds possess potent antioxidant, anti-inflammatory, antidiabetic, antimicrobial and anticancer properties (Cioch et al., 2017). Their extracts have shown strong efficacy against pathogenic microorganisms and are associated with improvements in lipid metabolism, glucose regulation, cognitive function, and prevention of diet-induced obesity. Despite these benefits, *Vaccinium vitis-idaea* remains one of the least studied fruits within the Ericaceae family (Alam et al., 2018), with a commercial value still constrained due to the scarcity of improved cultivars and continued reliance on wild foraging. Nevertheless, the species' extreme cold tolerance, low nutrient requirements, long postharvest stability, and consistently elevated levels of bioactive compounds highlight lingonberry's strong potential for expanded cultivation and the development of value-added functional food products (Lee and Finn, 2012).

3.8 *Lycium barbarum*

Lycium barbarum L., commonly known as goji berry or wolfberry, is the most widely cultivated species within the genus *Lycium*, which also includes *L. ruthenicum*, *L. dasystemum*, and *L. intricatum*, grown across Central Asia, Southern Africa, and parts of the Americas and Australia (Boulila and Bejaoui, 2015). Among these, *L. barbarum* dominates global cultivation due to its superior yield potential, richer polysaccharide profile, long-standing use in traditional Chinese medicine, and consistently high commercial demand. The shrubs grow 1–3 m tall and are highly tolerant of drought, intense sunlight, and wide temperature fluctuations, thriving in well-drained soils with pH 6–8 and showing remarkable adaptability to marginal, arid, and desertification-prone landscapes (Atakulova and Kizi-Valiyeva, 2025). The plant produces bright orange-red, ellipsoid berries that have been consumed for over 2,000 years not only for their taste, but also for their health properties. Today, the hepatoprotective, nephroprotective, immunomodulatory, and general tonic properties are well renowned (Skenderidis et al., 2022). Goji fruits are consumed fresh, dried, or used in juices, wines, teas, sauces, and a variety of functional foods. Traditional Chinese medicine attributes additional benefits to the berries, including support for vision, delay of premature greying of hair, aiding

infertility management, and alleviating fatigue, abdominal discomfort, cough, headaches, and urinary complaints (Amagase and Farnsworth, 2011; Yao et al., 2018; Byambasuren et al., 2019). Leaves are also used medicinally for liver protection, fever, dizziness, and eye disorders (Byambasuren et al., 2019; Lei et al., 2022). A notable but underexploited component of *Lycium* processing is its seed fraction, which constitutes 15%–20% of fresh fruit mass (Konarska, 2018) and is nutritionally rich, containing 46.5% carbohydrates, 18%–22% oil, 2%–6% polyphenols, 7.78% polysaccharides, 12%–15% proteins, and essential minerals (Zhao et al., 2018; Zhang X. X. et al., 2022). Despite this richness, seeds are usually discarded or used as low-value feed, representing a major opportunity for value addition. With its exceptional climatic resilience, diverse bioactive composition, and rapidly expanding global market for functional, nutrient-dense berries, *L. barbarum* represents a highly promising crop for sustainable production systems and the development of high-value nutritional products.

3.9 Cornus mas

Cornus mas L., commonly known as Cornelian cherry, is a hardy fruit-bearing dogwood native to Southeast Europe and West Asia, traditionally growing in temperate climates and thriving on dry, rocky, and nutrient-poor soils. The species shows remarkable ecological resilience, tolerating drought, frost, and high-altitude environments up to 1,400 m (Bayram and Ozturkcan, 2020). It grows slowly, can live up to 300 years, and shows high resistance to drought and frost (Kazimierski et al., 2019). Cornelian cherry grows to a maximum height of about 7–8 m (Demir and Kalyoncu, 2003) and can adapt well to adverse environmental conditions and is resistant to pests and diseases. Although long used in regional cuisines and folk medicines of Turkey, Romania, Bulgaria, Poland, and Iran, the species has remained underutilized due to limited domestication and reliance on wild foraging. However, recent evaluations have shown that orchard cultivation can increase productivity dramatically from 2.8 to 10 kg per wild shrub to nearly 80 kg per cultivated tree (Klimenko, 2004), highlighting its strong economic potential compared to conventional temperate fruit crops. Nutritionally, the fruits are rich in vitamin C, polyphenols, flavonoids, anthocyanins, and iridoids, providing potent antioxidant, anti-inflammatory, cardioprotective, hepatoprotective, and neuroprotective effects (Sevindik et al., 2024). These bioactive compounds, including gallic and ursolic acids, offer significant functional value in an era of rising demand for natural health-promoting foods. Though traditionally processed into jams, syrups, liquors and medicinal preparations, the fruits are now gaining interest in the functional food industry, where extracts have been shown to enhance the antioxidant stability of beverages and value-added products without compromising consumer acceptance. With its exceptional adaptability, high nutritional and phytochemical richness, long lifespan, and increasing market demand for natural antioxidants, *Cornus mas* represents a promising fruit species for expanding sustainable cultivation and developing new functional and nutraceutical product lines.

3.10 Physalis peruviana

Physalis peruviana L., commonly known as goldenberry or cape gooseberry, is a hardy Andean fruit species that has recently gained

global attention due to its exceptional adaptability, nutritional value, and expanding market potential. Native to the high-altitude regions of Peru, Ecuador, and Colombia, the species grows successfully across a wide ecological range from temperate climates to tropical highlands and tolerates poor, well-drained soils, moderate drought and fluctuating temperatures, making it well suited for low-input and marginal-area cultivation (Puentes et al., 2011). The plant is a short-lived perennial or annual shrub (0.6–1.8 m) that produces distinctive orange-gold berries enclosed in a papery calyx, which protects the fruits from pests, physical damage, and climatic stress and contributes to their long shelf life, extending up to 1 month with the husk. Goldenberry fruits are rich in bioactive compounds including carotenoids, polyphenols, vitamins A, C, and B-complex, minerals, and dietary fibre, and are associated with antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and immunomodulatory properties (Yamika et al., 2019; Prat and Sáenz, 2024). Traditionally consumed fresh, dried, or processed into jams, juices, sauces, and confectionery, the fruit is now recognized as a functional ingredient due to its balanced sweet-acid flavour, high pectinase activity, and strong global consumer appeal. The species' ability to grow in nutrient-poor soils, its protection by calyx during development (Añibarro-Ortega et al., 2025), low fertilizer requirements (Puentes et al., 2011) and strong postharvest longevity (Ozcelik et al., 2024) make *Physalis peruviana* an economically attractive crop for diversification.

3.11 Amelanchier spp.

The genus *Amelanchier* belongs to the Rosaceae family and according to the World Flora Online (WFO) database, it currently comprises 27 known accepted species (WFO, 2025). *Amelanchier* spp., commonly known as serviceberry, shadbush, or Saskatoon berry (STB), comprises hardy perennial shrubs and small trees native to Canada and the northern United States, with naturalized populations now present across Europe, Africa, and eastern Asia (Lavola et al., 2012). The genus is notable for its exceptional ecological adaptability, thriving across diverse soils and climates and displaying high genetic variability with frequent natural hybridization (Seeram, 2008; Stalažs, 2021). Among the species, *Amelanchier alnifolia* is the most commercially important, widely cultivated in Canada, where mature orchards yield 3,000–4,000 pounds per acre and national production recently exceeded 689 metric tons (Li et al., 2025). The shrubs begin bearing fruit 3–5 years after planting and reach full productivity by 6–8 years (Rop et al., 2013). Saskatoon berries are small dark-purple pomes rich in polyphenols, flavonoids, triterpenoids, polysaccharides, and essential amino acids, contributing to strong antioxidant, anti-inflammatory, antidiabetic, anti-atherosclerotic, anticancer, antimicrobial, and neuroprotective activities (Szpadzik and Krupa, 2021; Asyakina et al., 2022; Dăescu et al., 2024). However, the species historically valued by Indigenous communities for treating digestive disorders, colds, inflammation, and general ailments, is now gaining scientific and industrial interest due to its dense phytochemical profile and suitability for functional foods and nutraceuticals. The fruits are consumed fresh, dried, or processed into juices, syrups, wines, jams, and baked goods (Szpadzik and Krupa, 2021). These phytochemicals enhance the

functional potential of STB and can be used as ingredients in functional foods and pharmaceuticals to improve human health. STB contains all essential amino acids and nine non-essential amino acids (among them, cysteine, tyrosine, and arginine) (Master and Macedo, 2021). As a result, the demand for these derivatives is likely to increase, providing opportunities for the development of high-value STB-derived products. A comparative overview of the nutritional, agronomic, and commercialization attributes of these species is presented in Table 1.

4 Comparative nutritional content of major and underutilized berry fruits

Major berry fruits such as strawberry, blackberry, raspberry, cranberry, and blueberry are widely consumed and valued for their consistent availability and balanced nutritional profiles. On a fresh weight basis, these berries generally provide low to moderate nutrient levels. Strawberries supply approximately 32 kcal/100 g, 0.67 g protein, 7.68 g carbohydrates, 45–58.8 mg/100 g vitamin C, 153 mg/100 g potassium, and 16 mg/100 g calcium. Similarly, raspberries, cranberries, and blueberries provide vitamin C (26.2, 14.0, and 9.7 mg/100 g), iron (0.69, 0.23, and 0.28 mg/100 g), zinc (0.42, 0.09, and 0.16 mg/100 g), copper (0.09, 0.056, and 0.057 mg/100 g), protein (1.20, 0.46, and 0.74 g/100 g), and potassium (151, 80, and 77 mg/100 g), respectively. In contrast, underutilized berry species frequently exhibit substantially higher concentrations of essential nutrients. *Hippophae rhamnoides* contains approximately 370% higher vitamin C than strawberry (275 vs. 58.8 mg/100 g fresh weight) (Stobdan et al., 2010) and provides markedly greater levels of iron (4.4 mg/100 g), representing more than a five-fold increase compared with raspberry (Saeidi et al., 2016). Mulberry species also demonstrate pronounced nutritional superiority; *M. nigra* contains up to 60-fold higher iron than raspberry and nearly 12-fold higher potassium than blueberry on a fresh weight basis (Owon et al., 2016). Similarly, *Cornus mas* exhibits exceptionally high potassium content (>3,500 mg/100 g), corresponding to over 40-fold higher levels than blueberry (Dokoupil and Řezníček, 2012), while its juice provides appreciable amounts of calcium and trace minerals such as iron, zinc, and manganese (Krośniak et al., 2010).

Beyond basic nutrients, underutilized berries are further distinguished by their antioxidant composition. In *H. rhamnoides*, β -carotene constitutes approximately 15%–55% of total carotenoids, reaching 100–500 mg/100 g in the pulp (Nybom et al., 2023), which is several orders of magnitude higher than the β -carotene content of strawberry (≈ 7 μ g/100 g) (Bezerra et al., 2024). Likewise, strawberries and blueberries contribute approximately 33–38 and 40–44 mg catechin equivalents (CE)/100 g of total flavonoids, respectively (De-Souza et al., 2014), whereas *H. rhamnoides* contains up to 65% higher flavonoid levels on a fresh weight basis (Liu et al., 2021). Therefore, while major berries remain important for routine consumption, underutilized berry species consistently demonstrate superior micronutrient and antioxidant density, particularly in terms of vitamin C, potassium, iron, carotenoids, and flavonoids. A detailed overview of secondary metabolites, including anthocyanins, phenolic acids, polyphenols, carotenoids, and lipid-derived molecules, is presented in Tables 2, 3, 4 and 5. Whilst the

Figure 3 depicts the most representative compounds, that have been found in literature. The anthocyanins, part of the flavonoid compounds class, could be characterized by the presence of sugar group, bound to an anthocyanidin molecule (anthocyanin glycosides). In detailed, the anthocyanidin is composed by a flavylium cation core (Wang S. L. et al., 2024). The lipids are a group of hydrophobic or amphiphilic molecules, and the fatty acids (FA) are a consistent part of this broad group. Every FA is composed of a carboxylic acid with an aliphatic chain (De Carvalho and Caramujo, 2018) and here some of the most abundant fatty acids within the different botanical parts, are oleic acid and linoleic acid, also classified respectively as monounsaturated omega-9 fatty acid and omega-6 fatty acid. The phenolic acid molecule is recognized by the aromatic benzene ring with hydroxyl group bounds (-OH) and a carboxylic acid function (Al Jitan et al., 2018). The polyphenols are chemically characterized by one or multiple aromatic rings with hydroxyl groups (Singla et al., 2019). The carotenoids are chemically recognised as tetraterpenoids (C40), and composed by isoprene units (Maoka, 2020). Finally, the tocopherol group is also known as vitamin E class of compounds (Ali et al., 2022). While the previous sections summarize the diversity and distribution of secondary metabolites across different botanical parts of underutilized berry species, these compounds are also associated with a broad range of experimentally validated biological activities. Numerous *in vitro*, *in vivo*, and preclinical studies have linked berry-derived polyphenols, carotenoids, and lipid fractions to antioxidant, anti-inflammatory, antidiabetic, cardioprotective, antimicrobial, and neuroprotective effects. To synthesize this functional evidence, the experimentally reported biological effects of selected underutilized berry species are summarized in Table 6.

ABTS, 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid); FRAP, ferric reducing antioxidant power; GAE, gallic acid equivalents; FW, fresh weight; DW, dry weight; HFD, high-fat diet; NAFLD, non-alcoholic fatty liver disease; ROS, reactive oxygen species; MDA, malondialdehyde; SOD, superoxide dismutase; GPx, glutathione peroxidase; NOS, nitric oxide synthase; iNOS, inducible nitric oxide synthase; COX-2, cyclooxygenase-2; TBARS, thiobarbituric acid reactive substances; PLE, pressurized liquid extraction; MAE, microwave-assisted extraction; SFE-CO₂, supercritical fluid extraction using carbon dioxide; USE, ultrasound-assisted solvent extraction; SE, solvent extraction; AuNPs, gold nanoparticles; AgNPs, silver nanoparticles; IC₅₀, concentration causing 50% inhibition; TE, Trolox equivalents; HSV-1, herpes simplex virus type 1; MPTP, 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine; LID, levodopa-induced dyskinesia.

5 Challenges

Despite their promising nutritional value and ecological resilience, the large-scale adoption of underutilized berry species remains constrained by several structural, agronomic, and market-related limitations. A major barrier is the absence of efficient and integrated supply chains. Many of these berries such as *Amelanchier alnifolia*, *Cornus mas*, *Aronia melanocarpa*, and *Physalis peruviana* are primarily harvested from smallholder systems or semi-wild stands, where production volumes are inconsistent and geographically dispersed. Consequently, postharvest operations

TABLE 1 Comparative overview of nutritional, agronomic and commercialization attributes of underutilized berry species.

Berry species	Nutritional/bioactive strength	Major health relevance	Abiotic stress tolerance	Commercial readiness/Value-chain potential
<i>Ribes rubrum</i> and <i>Ribes nigrum</i>	Anthocyanins, flavonols, phenolic acids	Antioxidant, antimicrobial, functional foods	Moderate (cool climates)	Semi-commercial; juices, jams, concentrates, powders
<i>Aronia</i> spp.	Very high polyphenols and anthocyanins	Anti-inflammatory, cardiometabolic health	High (cold, marginal soils)	Commercially emerging; nutraceuticals, extracts
<i>Hippophae rhamnoides</i>	Vitamins (C, E), carotenoids, fatty acids (ω -7)	Cardioprotective, dermatoprotective	Very high (drought, salinity, poor soils)	Commercial; oils, beverages, cosmetics, land restoration
<i>Lonicera caerulea</i>	Anthocyanins (C3G), vitamin C	Antioxidant, vascular and neuroprotective	Very high (extreme cold)	Emerging; fresh fruit, functional foods
<i>Sambucus nigra</i>	Anthocyanins, flavonols, vitamins	Antiviral, immunomodulatory	Moderate-high	Commercial; syrups, natural colorants
<i>Morus</i> spp.	Anthocyanins, amino acids, flavonoids	Antidiabetic, cardioprotective	High (drought-tolerant, adaptable)	Commercial-regional; juices, molasses, functional foods
<i>Vaccinium vitis-idaea</i>	Polyphenols, proanthocyanidins	Antioxidant, antimicrobial, metabolic health	High (cold, nutrient-poor soils)	Emerging; jams, extracts, wild harvest
<i>Lycium barbarum</i>	Polysaccharides, carotenoids, flavonols	Immunomodulatory, hepatoprotective	Very high (arid, saline regions)	Commercial; dried fruits, supplements
<i>Cornus mas</i>	Vitamin C, anthocyanins, iridoids	Anti-inflammatory, cardiometabolic	High (drought, rocky soils)	Emerging; syrups, extracts, functional foods
<i>Physalis peruviana</i>	Carotenoids, withanolides, polyphenols	Antidiabetic, immunomodulatory	Moderate-high (poor soils, drought)	Commercially emerging; fresh and processed
<i>Amelanchier alnifolia</i>	Polyphenols, amino acids, triterpenoids	Antioxidant, neuroprotective	High (cold, variable soils)	Semi-commercial; juices, dried fruits

Abiotic stress tolerance and commercial readiness are summarized based on dominant trends reported in the literature and may vary among cultivars and production systems.

including grading, packaging, cold storage, and long-distance transportation remain poorly developed. This lack of infrastructure severely restricts their availability in mainstream retail channels, especially given that several of these fruits (e.g., *Physalis peruviana* without calyx) possess short shelf lives and require specialized handling strategies to minimize losses.

Another critical challenge is the considerable research gap surrounding cultivation, breeding, and genetic improvement of these crops. Compared with major commercial berries like strawberry, blueberry, and raspberry, underutilized species have received minimal scientific attention. For many genera such as *Lonicera*, *Lycium*, *Cornus*, and *Amelanchier* information on genotype performance, stress physiology, optimized fertilization regimes, pruning strategies, and pest management remains limited. The absence of structured breeding programs results in low-yielding or genetically heterogeneous plant materials being used in cultivation, which restricts productivity and complicates large-scale orchard establishment. Breeding efforts for enhanced fruit size, uniform ripening, disease resistance, and mechanical harvestability are still at a nascent stage, slowing commercialization efforts.

Market-related constraints further limit the transition of these berries from niche commodities to mainstream horticultural crops at regional and global scales. Value chain actors such as processors, exporters, retailers, and nutraceutical companies often have limited familiarity with these species, resulting in poor market integration and insufficient price incentives for growers. Consumers, too, often prefer well-established fruits, and the limited culinary familiarity or perceived complexity of preparation (e.g., the astringency of *Aronia*,

the seediness of *Lycium*, or the tartness of *Cornus mas*) restricts their acceptance beyond traditional communities. Weak demand feedback loops discourage farmers from expanding cultivation, creating a cycle of low production and low market visibility.

In addition to agronomic, technical, and market-related constraints, socio-economic factors also limit the commercialization of underutilized berry crops. In many production regions, insecure land tenure discourages smallholder farmers from investing in perennial berry species that require several years to reach full productivity. Moreover, women frequently play a central role in berry harvesting, processing, and informal marketing, yet often face limited access to land ownership, credit, extension services, and decision-making power. These structural constraints can significantly reduce adoption rates and must be addressed alongside technological innovations to ensure inclusive and equitable development of emerging berry value chains.

Knowledge gaps regarding nutritional and health-promoting properties also contribute to the underutilization of these berries. Although preliminary studies highlight their rich content of polyphenols, anthocyanins, carotenoids, and biologically active metabolites, systematic clinical validation and translational research remain scarce. The absence of standardized analytical methodologies, variability in phytochemical profiles across ecotypes, and limited regulatory frameworks for functional claims further restrict their integration into functional food sectors, pharmaceutical formulations, and nutraceutical industries.

Furthermore, the large-scale commercialization of wild or marginal berry species may raise ecological concerns if not

TABLE 2 Root-derived secondary metabolites reported in selected underutilized berry species.

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Ribes nigrum</i>	Root	—	—	Not reported	—
<i>Ribes rubrum</i>	Root	—	—	Not reported	—
<i>Aronia</i> spp.	Root	—	—	Not reported	—
<i>Hippophae rhamnoides</i>	Root	Flavonoids	Isorhamnetin Pentamethylquercetin Syringetin	Identified	Liu et al. (2021)
<i>Lonicera caerulea</i>	Root	—	—	Not reported	—
<i>Sambucus nigra</i>	Root	—	—	Not reported	—
<i>Morus</i> spp.	Root	Flavonoids	Kuwanon S Eudraflavone B hydroperoxide leachianone G	Identified	Singh et al. (2013) ; Jo et al. (2014) ; Batiha et al. (2023)
<i>Vaccinium vitis-idaea</i>	Root	—	—	Not reported	—
<i>Lycium barbarum</i>	Root	—	—	Not reported	—
<i>Cornus mas</i>	Root	—	—	Not reported	—
<i>Physalis peruviana</i>	Root	Alkaloids	(+)-physoperruvine Cuscohygrine	Identified	Aneja et al. (2025)
		Withanolides	Withaperurvin E Withaperurvin F Withaperurvin G Withaperurvin H		Tarun and Biswajit, (2023) ; Aneja et al. (2025)
<i>Amelanchier alnifolia</i>	Root	—	—	Not reported	—

“Not reported” indicates the absence of published data on root-derived secondary metabolites for the corresponding species; dash (–) denotes categories for which no information has been reported, highlighting existing research gaps rather than the absence of bioactive potential.

properly managed. Potential risks include overharvesting of wild populations, habitat disturbance, unintended spread beyond cultivation areas, and loss of local genetic diversity. However, evidence from previously domesticated berry crops such as *Vaccinium corymbosum* and *Rubus idaeus* demonstrates that transitioning from wild collection to controlled cultivation can substantially reduce pressure on natural ecosystems. The adoption of regulated production systems, including nursery-based propagation, orchard establishment, pot cultivation, and optimized fertigation, allows growers to minimize land-use change, water inputs, and chemical dependency. Furthermore, integration into organic and low-input farming systems can support biodiversity conservation while enabling sustainable commercialization of underutilized berry species.

Additionally, postharvest technologies and processing innovations for many of these species are underdeveloped. Unlike commercial berries with established protocols for freezing, drying, juice extraction, and concentration, underutilized berries often lack optimized procedures for preserving bioactive compounds or ensuring product stability during storage. This limits their competitiveness in high-value markets such as natural pigments, antioxidant supplements, fermented beverages, or minimally processed snacks. All these challenges underscore the need for a coordinated research, socio-economic, policy, and infrastructural framework to

unlock the full potential of underutilized berry crops, which are otherwise exceptionally promising for climate-resilient, nutrient-dense food systems.

6 Future prospects

6.1 Development of improved cultivars

Advancing genomic, transcriptomic, and metabolomic tools can accelerate breeding programs for underutilized berries, enabling the selection of genotypes with superior yield, enhanced stress tolerance, and optimized phytochemical profiles for functional food applications.

6.2 Integration into climate-resilient agriculture

As climate variability intensifies, underutilized berry species offer substantial potential for integration into diversified, low-input farming systems, agroforestry models, particularly in regions affected by water scarcity and soil salinity. Several taxa reviewed here, including *Hippophae rhamnoides*, *Lycium barbarum*, and *Cornus mas*, exhibit strong tolerance to drought, salinity, and nutrient-poor soils, enabling stable productivity under conditions

TABLE 3 Seed-derived secondary metabolites reported in selected underutilized berry species.

Species (genotype)	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Ribes nigrum</i>	Seeds	Fatty acid	γ-linoleic acid	Identified	Nour et al. (2013)
<i>Ribes rubrum</i>	Seeds	—	—	Not reported	—
<i>Aronia</i> spp.	Seeds	Lipids and fatty acids	Linoleic acid Oleic acid Phospholipids Sterols Tocopherols	Identified	Piasecka et al. (2021) Piras et al. (2024)
		Flavanols	Epicatechin		Piras et al. (2024)
		Flavonoids	Rutin Quercetin-3-glucoside		Piras et al. (2024)
		Anthocyanins	Cyanidin-3-galactoside Cyanidin-3-arabinoside Cyanidin-3-xyloside Cyanidin-3-glucoside		Piras et al. (2024)
<i>Hippophae rhamnoides</i>	Seeds	Phenolic compounds	p-Hydroxybenzoic acid Trans-cinnamic acid Protocatechuic acid O-methylgallic acid Hydroxygallic acid Ferulic acid Caffeoylquinic shikimate derivative Apigenin (+)-Catechin Quercetin-3-O-(6''-benzoyl)-β-galactoside Catechin-O-dihexoside Ellagic acid derivative II Ellagic acid pentoside Ellagic acid derivative IV	Identified	Ślawińska and Olas, 2023; Ślawińska et al. (2025)
<i>Lonicera caerulea</i>	Seeds	—	—	Not reported	—
<i>Sambucus nigra</i>	Seeds	Fatty acids	α-linolenic acid	Identified	Vlaicu et al. (2025)
<i>Morus</i> spp.	Seeds	Fatty acids	Linoleic acid Palmitic acid Oleic acid Stearic acid	Identified	Jan et al. (2021)
<i>Vaccinium vitis-idaea</i>	Seeds	—	—	Not reported	—
<i>Lycium barbarum</i>	Seeds	Fatty acids	Linoleic acid Oleic acid Palmitic acid Stearic acid γ-Linolenic acid	Identified	Guoliang et al. (2011); Zhang X. X. et al., 2022
		Polyphenols	Quercetin Kaempferol Isorhamnetin Chlorogenic acid Gallic acid		Magiera and Zaręba, (2015)
		Polysaccharides	Rhamnose Xylose Arabinose Galactose Mannose Glucose		Cao et al. (2022)
		Tocopherols	α-Tocopherol γ-Tocopherol		Liu et al. (2019)
<i>Cornus mas</i>	Seeds	Fatty acids	Linoleic acid	Identified	Brindza et al. (2009); Tiptiri-Kourpeti et al. (2019); Antoniewska-Krzeska et al. (2022)

(Continued)

TABLE 3 Continued

Species (genotype)	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Physalis peruviana</i>	Seeds	Fatty acids	Linoleic acid Oleic acid Palmitic acid	Identified	Ramadan and Mörsel (2003); Puente et al. (2011); Popova et al. (2021)
		Phytosterols	Campesterol β-sitosterol Stigmasterol		Ramadan and Mörsel (2003); Puente et al. (2011)
		Tocopherols	β-Tocopherol γ-Tocopherol γ-Tocotrienol δ-Tocopherol		Popova et al. (2020); Popova et al. (2021)
<i>Amelanchier</i> spp.	Seeds	Cyanogenic glycosides	Amygdalin Prunasin	Identified	Saunoriūtė et al. (2025a)

“Not reported” indicates the absence of published data on seed-derived secondary metabolites for the corresponding species, highlighting existing research gaps rather than the absence of bioactive potential.

where conventional fruit crops fail (Ilhan et al., 2021; Grabacka et al., 2024; Liu et al., 2024). Their deep or extensive root systems, efficient water-use strategies, and stress-induced accumulation of protective secondary metabolites make these species especially suitable for agroforestry systems, land reclamation, and the productive use of marginal or degraded agricultural landscapes.

6.3 Expansion of value-added processing chains

Novel technologies such as cold-press extraction, freeze-drying, encapsulation, and fermentation present opportunities to transform underutilized berries into high-value nutraceuticals, beverages, pigments, and preservative-free functional ingredients.

6.4 Strengthening market infrastructure and global trade

Establishing organized supply chains, producer cooperatives, and standardized quality and safety protocols will enhance domestic and international market entry, encouraging commercialization beyond niche or regional markets.

6.5 Advances in postharvest management

Research on shelf-life extension, non-destructive quality monitoring, eco-friendly packaging, and optimized storage conditions can minimize losses and improve economic returns for growers and processors. Importantly, product-specific processing strategies must be optimized, as different processing pathways can markedly influence the retention of bioactive compounds. For instance, blackcurrant processing generates pomace rich in dietary fibre, organic acids, vitamins, and phenolic compounds, making it suitable for incorporation into functional food formulations, whereas large-scale juice production may result in substantial losses of anthocyanins and other phenolics (Koponen et al., 2008). In contrast, blackcurrant powder produced *via* freeze-drying has demonstrated high stability

of bioactive compounds and versatile functionality as a natural additive in bakery and dough-based food products, highlighting the importance of tailoring postharvest and processing systems to specific end uses (Ejaz et al., 2023).

6.6 Policy support and farmer adoption

Incentive-driven policies, extension programs, and community-based cultivation models can substantially enhance the adoption of underutilized berry crops in marginal regions, contributing to livelihood diversification and rural income stability. However, regulatory approval represents a critical hurdle for the commercialization of less known or uncommon berry species, particularly when products are positioned as functional foods, nutraceuticals, or dietary supplements. In the European Commission, (2015) on novel foods governs the market entry of berry-derived ingredients lacking documented consumption prior to 1997 and requires comprehensive pre-market safety assessment by the European Food Safety Authority (EFSA). This process can be time-consuming and resource-intensive, often posing a barrier for small producers and emerging value chains. In addition, any nutrition or health claims associated with berry-derived products must be scientifically substantiated and authorized under European Commission, (2006), which necessitates robust compositional data and, in many cases, human clinical evidence.

In the United States, novel berry-derived products marketed as dietary supplements are regulated under the Dietary Supplement Health and Education Act (DSHEA), with manufacturers responsible for ensuring product safety through Generally Recognized as Safe (GRAS) status or, for ingredients not marketed before 1994, submission of a New Dietary Ingredient (NDI) notification to the Food and Drug Administration (U.S. Food and Drug Administration, 1994). The lack of standardized phytochemical profiles, variability among ecotypes, and limited clinical validation for many underutilized berries can complicate these regulatory processes and delay market entry. Addressing these challenges through early regulatory planning, harmonized analytical protocols, and coordinated clinical research will be essential to

TABLE 4 Leaves-derived secondary metabolites reported in selected underutilized berry species.

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Ribes nigrum</i>	Leaves	Antioxidants	Quercetin Kaempferol Prodelphinidins Chlorogenic acid Caffeic acid Gallic acid Ferulic acid Gentisic acid	Identified	Ferlemi and Lamari, (2016), Tabart et al. (2012), Teleszko and Wojdylo, (2015)
<i>Ribes rubrum</i>	Leaves	—	—	Not reported	—
<i>Aronia</i> spp.	Leaves	Anthocyanins	Anthocyanidins Cyanidin-3-O-galactoside Peonidin-3-O-galactoside	Identified	Olas et al. (2008); Xie et al. (2017); Do-Thi and Hwang, (2018)
<i>Hippophae rhamnoides</i>	Leaves	Anthocyanins and flavonoids	Leukoanthocyanins Tannins Organic acids Flavonoids	Identified	Kovaleva et al. (2023); Kovaleva et al. (2025)
<i>Lonicera caerulea</i>	Leaves	Flavonoids	Quercitrin Kaempferol-3-O- α -L-rhamnoside Quercetin 3-O-(3''-O-acetyl)- α -L-rhamnoside Kaempferol	Identified	Wang J. et al. (2024)
		Terpenoids	Loncaeranol A Neroplomacrol Nortirucallane A		Wang J. et al. (2024)
<i>Sambucus nigra</i>	Leaves	Fatty acids	Oleic acid Linoleic acid Alpha-linolenic acid Octadecatetraenoic acid Eicosadienoic acid Docosadienoic acid	Identified	Vlaicu et al. (2025); Ferreira et al., 2022b
		Carotenoids	Lutein Zeaxanthin Canthaxanthin Astaxanthin		Vlaicu et al. (2025); Ferreira et al., (2022b)
<i>Morus</i> spp.	Leaves	Flavonoids	Rutin Isoquercitrin Quercetin-3-(6-malonyl) glucoside Quercetin Astragalin (kaempferol-3-O-glucoside) Kaempferol-7-O-glucoside	Identified	Zafar et al. (2013); Jiang et al. (2014)
		Coumarins	5,7-Dihydroxycoumarin 7-methyl ether		Zou et al. (2014)
		Alkaloids	1-Deoxynojirimycin (DNJ) 2-O- α -D-galactopyranosyl deoxynojirimycin 4-O- β -D-glucopyranosyl deoxynojirimycin		Jiang et al. (2014); Cao et al., 2022
<i>Vaccinium vitis-idaea</i>	Leaves	Triterpenoids	Oleanolic acid Ursolic acid α -Amyrin β -Amyrin Betulin Lupeol	Identified	Szakiel et al. (2012)
		Phenolic compounds	Flavonols Catechin Epicatechin Hydroxycinnamic acids		EK et al. (2006); Bujor et al. (2018)

(Continued)

TABLE 4 Continued

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Lycium barbarum</i>	Leaves	Phenolic acids	Caffeic acid Chlorogenic acid p-Coumaric acid Ferulic acid Gentisic acid Salicylic acid Sinapic acid Syringic acid Vanillic acid Vanillin	Identified	Dong et al. (2011); Mocan et al. (2015); Pollini et al. (2020); Dogan et al. (2023)
		Flavonoids	Isoquercitrin Kaempferol Rutin Quercitrin Quercetin		Dong et al. (2011); Mocan et al. (2015); Pollini et al. (2020)
<i>Cornus mas</i>	Leaves	Flavonoids	Quercetin derivatives Kaempferol derivatives	Identified	Badalica-Petrescu et al. (2014); Dinda et al. (2016)
		Antioxidant compounds	Total phenolics Total flavonoids		Stanković et al., (2014); Milenković-Andjelković et al. (2015)
<i>Physalis peruviana</i>	Leaves	Withanolides	23-Hydroxyphysalolactone Isoperulactone 3-O-β-D-glucopyranoside Perulactone 3-O-β-Dglucopyranoside Physalolactone B-3- O-β-Dglucopyranoside 4-Deoxyphysalolactone	Identified	Aneja et al. (2025)
		Flavonoids	Catechin Epicatechin Chlorogenic acid Cyanidin glycosides Quercetin glycosides Rutin Isoquercitrin Hyperoside Astragalin Afzelin Kaempferol glycosides Isorhamnetin glycosides		Saunoriūtė et al. (2025b)
		Phenolic acids	Neochlorogenic acid Chlorogenic acid 4-O-caffeoylquinic acid Dicaffeoylquinic acids		Męczarska et al., (2017); Saunoriūtė et al. (2025b)

“Not reported” indicates the absence of published data on leaf-derived secondary metabolites for the corresponding species, highlighting existing research gaps rather than the absence of bioactive potential.

reduce market uncertainty, encourage private investment, and facilitate farmer participation in emerging berry value chains.

7 Pharmacological validation and clinical research

A growing body of literature supports the pharmacological potential of underutilized berry species, extending beyond traditional use into experimentally validated health applications. As demonstrated by the phytochemical profiles summarized in the present review, multiple botanical parts of these plants contain bioactive compounds with antimicrobial, anti-inflammatory, antidiabetic, and antioxidant activities.

Blackcurrant (*Ribes nigrum*) fruits and seeds, characterized by high flavonoid content, have demonstrated notable antibacterial activity, supporting their application in food preservation, pharmaceutical formulations, and active packaging systems. Recent studies have also explored encapsulated blackcurrant formulations as dietary supplements, reporting improved bioavailability, controlled release, and enhanced stability of bioactive compounds (Wu H. et al., 2021; Pedisić et al., 2025). Importantly, the quality and quantity of phytonutrients are strongly influenced by extraction and processing techniques, including solvent-based, microwave-assisted, ultrasound-assisted, pulsed electric field, sonication, and enzyme-assisted methods (Ejaz et al., 2023). Likewise, red currant (*Ribes rubrum*) berries have been investigated in nanoparticle-based formulations, demonstrating promising antimicrobial activity (Rizwana et al., 2022).

TABLE 5 Fruit-derived secondary metabolites reported in selected underutilized berry species.

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Ribes nigrum</i>	Fruits	Aurones	Aureusidin	Identified	Sandell et al. (2009)
		Flavonols	Quercetin Quercetin-3-O-glucoside Quercetin-3-O-arabinoside Quercetin-3-O-galactoside Quercetin-3-O-rutinoside Kaempferol Kaempferol-3-O-glucoside Kaempferol-3-O-rutinoside Rutin Hyperoside Myricetin Myricetin-3-O-glucoside Myricetin-3-O-galactoside Myricetin-3-O-arabinoside Myricetin-3-O-rutinoside Dihydroquercetin		Sandell et al. (2009); Staszowska-Karkut and Materska, 2020; Nanashima et al. (2020); Bilici, (2021); Ejaz et al. (2023); Izteleuova et al. (2025)
		Flavan-3-ols	Epigallocatechin		Zhao et al. (2021)
		Anthocyanins	Cyanidin-3-O-glucoside Pelargonidin Pelargonidin-3-O-glucoside Pelargonidin-3-O-rutinoside Peonidin Peonidin-3-O-glucoside Peonidin-3-O-rutinoside Cyanidin Delphinidin Petunidin chloride Malvidin Malvidin-3-O-glucoside Cyanidin-3-O-arabinoside Cyanidin-3-O-rutinoside Delphinidin-3-O-rutinoside Delphinidin-3-O-glucoside		Slimestad and Solheim, (2002); Zhang et al. (2023)
		Phenolic acids	Neochlorogenic acid Cryptochlorogenic acid Protocatechuic acid Dihydroxyphenylacetic acid <i>p</i> -Hydroxybenzoic acid 4-Hydroxyphenylacetic acid Tannic acids		Staszowska-Karkut and Materska, 2020; Nanashima et al. (2020); Zhou, (2016)
		Fatty acids	Linoleic acid Palmitic acid Stearidonic acid Stearic acid Oleic acid		Miladinović et al. (2014)
<i>Ribes rubrum</i>	Fruits	–	–	Not reported	–
<i>Aronia</i> spp.	Fruits	Phenolic acids	Chlorogenic acid	Identified	Kavela et al. (2025); Thorakkattu et al. (2025)
		Flavanols	Epicatechin		
		Flavonoids	Rutin Quercetin-3-glucoside		
		Anthocyanins	Cyanidin-3-galactoside Cyanidin-3-arabinoside Cyanidin-3-xyloside Cyanidin-3-glucoside		

(Continued)

TABLE 5 Continued

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Hippophae rhamnoides</i>	Fruits	Phenolic compounds	p-Hydroxybenzoic acid Protocatechuic acid p-Coumaric acid O-methylgallic acid Ferulic acid Caffeoylquinic shikimate derivative Tri-O-caffeoylshikimic acid Apigenin Quercetin sulfate Catechin-O-dihexoside Ellagic acid derivative IV	Identified	Zhang et al. (2023); Danielski and Shahidi, (2024)
<i>Lonicera caerulea</i>	Fruits	Anthocyanins	Anthocyanidins Cyanidin 3,5-O-diglucoside Cyanidin-3-O-β-galactoside Cyanidin-3-O-glucoside Cyanidin-3-O-hexoside Cyanidin-3-O-rutinoside Delphinidin 3-O-Beta-D-sambubioside Delphinidin 3-O-β-galactoside Delphinidin 3-O-hexoside Delphinidin 3-O-rutinoside Delphinidin-3-O-(6''-O-acetyl) hexoside Peonidin 3-O-(6-O-p-coumaroyl) glucoside Peonidin 3-O-rutinoside Peonidin-3-O-glucoside Petunidin 3-O-(6-O-acetyl) glucoside	Identified	Fujita et al. (2020); Wang et al. (2018); Senica et al. (2020); Khattab et al. (2015); Auzanneau et al. (2018); Razgonova et al. (2025)
		Flavan-3-ol	(-)-Epicatechin gallate [(-)-Epicatechin-3-O-Gallate; L-epicatechin gallate] (Epi)-afzelechin derivative (Epi)-catechin (Epi)-catechin derivative 1 (Epi)-catechin derivative 2 (Epi)-catechin derivative 3 (epi)Catechin O-hexoside (Epi)-gallo catechin (Epi)gallo catechin-(epi)catechin dimer Catechin Epi afzelechin		Razgonova et al. (2025)
<i>Sambucus nigra</i>	Fruits	Carotenoids	Lutein Zeaxanthin Canthaxanthin	Identified	Vlaicu et al. (2025); Sidor and Gramza-Michałowska (2015)
		Tocopherols	α-tocopherol δ-Tocopherol γ-Tocopherol		Vlaicu et al. (2025)
		Anthocyanins	Cyanidin-3-sambubioside Cyanidin-3,5-diglucoside Cyanidin-3-sambubioside-5-glucoside Peonidin-3-sambubioside Pelargonidin-3-sambubioside		Lee and Finn, (2007); Schmitzer et al. (2010); Ulbricht et al. (2014)

(Continued)

TABLE 5 Continued

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Morus</i> spp.	Fruits	Organic acids	Malic acid Citric acid	Identified	Hussain et al. (2021); Wen et al. (2019)
		Anthocyanins	Cyanidin 3-glucoside Cyanidin 3-rutinoside Cyanidin 3,5-diglucoside Pelargonidin 3-glucoside Peonidin 3-glucoside Cyanidin 3-O-(6''-O- α -rhamnopyranosyl- β -D-glucopyranoside) Cyanidin 3-O-(6''-O- α -rhamnopyranosyl- β -D-galactopyranoside) Cyanidin 3-O- β -D-galactopyranoside Cyanidin 7-O- β -D-glucopyranoside Petunidin 3-O- β -D-glucopyranoside		Koca et al. (2008); Ramesh et al. (2014)
		Flavonols	Quercetin Quercetin 3-O-rutinoside Quercetin 3-O-glucoside Quercetin 3-O-galactoside Myricetin Kaempferol Kaempferol 3-O-glucoside Kaempferol 3-O-rutinoside		Ionica et al. (2017); Yuan and Zhao, (2017)
		Phenolic acids	Caffeic acid Chlorogenic acid Coumaric acid Ferulic acid Sinapic acid Trans-cinnamic acid		Ionica et al. (2017); Yuan and Zhao, (2017)
<i>Vaccinium vitis-idaea</i>	Fruits	Anthocyanins	Cyanidin-3-galactoside Cyanidin-3-arabinoside Cyanidin-3-glucoside	Identified	EK et al. (2006); Kowalska et al. (2019)
		Flavonols	Quercetin Quercetin-3-O-galactoside Quercetin-3-O-glucoside Quercetin-3-O-rutinoside Quercetin-3-O-rhamnoside Quercetin pentosides Quercetin-3-O-(HMG)-rhamnoside Kaempferol hexoside Kaempferol rutinoside Kaempferol-3-O-rhamnoside		Lehtonen et al. (2010); Mane et al. (2011)
		Flavanols	Catechin Epicatechin		Lehtonen et al. (2010)

(Continued)

TABLE 5 Continued

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Lycium barbarum</i>	Fruits	Phenolic acids	Caffeic acid p-Coumaric acid Ferulic acid Chlorogenic acid Fumaric acid Gallic acid Pyrogallol	Identified	Donno et al. (2015); Protti et al. (2017); Ozkan et al. (2018); Nzeuwa et al. (2022); Magalhães et al., 2022; Xu et al. (2022); Ju et al. (2023)
		Flavonols	Quercetin Isoquercetin Kaempferol-3-O-rutinoside Isorhamnetin Isorhamnetin-3-O-glucoside Isorhamnetin-3-O-rutinoside		
		Anthocyanins	Cyanidin chloride Cyanidin-3-O-glucoside Pelargonidin-3-O-glucoside Pelargonin chloride		Nzeuwa et al. (2022); Ju et al. (2023)
		Essential oil components	Acetic acid Hexadecanoic acid Ethyl lactate 3-Hydroxy-2-butanone Linoleic acid Myristic acid Ethyl hexadecanoate Hexanal (E)-2-Hexenal Nonanal Isoamylol 1-Hexanol 1-Octen-3-ol Ethyl octanoate o-Cymene d-Limonene Linalool β-Cyclocitral 2-Pentylfuran		Chen et al. (2015); Lu et al. (2017)
<i>Cornus mas</i>	Fruits	Polyphenols	Quercetin 3-O-robinobioside Quercetin 3-O-glucuronide Quercetin-3-O-xyloside Quercetin-3-O-rhamnoside Quercetin-3-O-glucoside Quercetin-3-O-galactoside Kaempferol 3-O-galactoside Kaempferol 3-glucoside Myricetin Myricetin 3-galactoside	Identified	Jurikova et al. (2025)
		Anthocyanins	Cyanidin-3-O-galactoside Cyanidin-3-O-glucoside Cyanidin-3-O-robinobioside Pelargonidin 3-O-galactoside Delphinidin 3-O-β-glucoside		Seeram et al. (2002); Antolak et al. (2017); Dzydzan et al. (2019); Świerczewska et al. (2019)
		Iridoids	Loganic acid Sweroside Cornuside Catalposide		Dzydzan et al. (2019); Perova et al. (2014); Sochor et al. (2014)
		Triterpenoids	Ursolic acid		Jayaprakasam et al. (2006)

(Continued)

TABLE 5 Continued

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
<i>Physalis peruviana</i>	Fruits	Carotenoids	β -carotene α -carotene β -cryptoxanthin	Identified	Fischer et al. (2000)
		Phytosterols	Campesterol β -sitosterol Stigmasterol Δ 5-avenasterol Lanosterol Δ 7-avenasterol Ergosterol		Ramadan and Mörsel (2003)
		Fatty acids	Linoleic acid Oleic acid Palmitic acid Stearic acid α -linolenic acid Dihomo- γ -linolenic acid		Ramadan and Mörsel (2003)
		Physalins	Physalin A Physalin B Physalin D Physalin F Physalin glycosides		Ramadan and Mörsel (2003); Puente et al. (2011)
		Withanolides	Withanolide E Withanolide S Withanolide C Withaperuvine		Lan et al. (2009)
			Physalolactone Withaphysanolide Physalactone Withaperuvine D Loliolid		
<i>Amelanchier alnifolia</i>	Fruits	Anthocyanins	Cyanidin-3-galactoside Cyanidin-3-glucoside Cyanidin-3-arabinoside Cyanidin-3-xyloside Cyanidin-3,5-diglucoside Peonidin-3-glucoside Delphinidin-3-glucoside Delphinidin-3-rutinoside Delphinidin-3-galactoside Petunidin-3-galactoside Petunidin-3-glucoside Malvidin-3-galactoside Malvidin-3-glucoside	Identified	Bakowska-Barczak and Kolodziejczyk, 2008; Burns-Kraft et al. (2008); Męczarska et al., 2017

(Continued)

TABLE 5 Continued

Species	Botanical part	Major chemical class	Representative compounds	Evidence status	References
		Flavonols	Quercetin-3-galactoside Quercetin-3-glucoside Quercetin-3-rutinoside Quercetin-3-arabinoside Quercetin-3-robinobioside Quercetin-3-vicianoside Quercetin dirhamnoside Kaempferol-3-galactoside Kaempferol-3-glucoside Kaempferol-3-rutinoside Kaempferol-3-arabinoside Kaempferol-3-rhamnoside		Mikulic-Petkovšek et al., 2020; Dăescu et al. (2024)
		Phenolic acids	Chlorogenic acid Neochlorogenic acid Cryptochlorogenic acid Caffeic acid p-Hydroxybenzoic acid Protocatechuic acid Ferulic acid Coumaric acid		Bakowska-Barczak and Kolodziejczyk, 2008; Lavola et al. (2012); Lachowicz et al. (2017); Męczarska et al., 2017
		Triterpenoids	Oleanolic acid Betulinic acid Ursolic acid		Lachowicz et al. (2017)
		Carotenoids	β-carotene Lutein Zeaxanthin		Mazza and Cottrell, (2008); Lachowicz et al. (2017)

“Not reported” indicates the absence of published data on fruit-derived secondary metabolites for the corresponding species; dash (–) denotes categories for which no information has been reported, highlighting existing research gaps rather than the absence of bioactive potential.

Among the reviewed species, *Aronia melanocarpa* has attracted particular attention for its anti-inflammatory, antimicrobial, antiviral, and antidiabetic properties, with intervention studies reporting reductions in blood glucose levels in individuals with diabetes mellitus (Lupascu et al., 2016). In addition, *Hippophae rhamnoides* and *Lycium barbarum* are supported by preclinical and clinical evidence demonstrating antioxidant, anti-inflammatory, cardiometabolic, immunomodulatory, and hepatoprotective effects, largely attributed to their rich vitamin, fatty acid, polysaccharide, and polyphenol profiles (Sharifi-Rad et al., 2024; Zhang et al., 2025). Similarly, *Sambucus nigra* and *Lonicera caerulea* have shown strong antioxidant, vascular, antiviral, and immunomodulatory activities (Bartak et al., 2020; Negreanu-Pirjol et al., 2023), while emerging studies on *Cornus mas* and *Physalis peruviana* report benefits related to glycemic control, lipid metabolism, and inflammatory regulation (Hosseinpour-Jaghdani et al., 2017; Añibarro-Ortega et al., 2025). Overall, while pharmacological evidence for several underutilized berry species is promising, further standardized clinical trials are required to support regulatory approval and large-scale functional food applications.

8 Utilization of underexplored botanical parts

Beyond fruits, several underutilized berry species possess botanically distinct parts such as seeds, leaves, and roots that represent valuable but still underexploited sources of bioactive compounds. Increasing

evidence indicates that whole-plant utilization can significantly enhance economic returns, reduce processing waste, and strengthen the sustainability of berry-based value chains.

Among the reviewed taxa, *Hippophae rhamnoides* exhibits exceptional whole-plant utilization potential. Its seed oil is rich in linoleic acid, linolenic acid, lauric acid, hexaenoic acid, and other unsaturated fatty acids with high nutritional and physiological relevance (Bouras et al., 2017). In addition, sea buckthorn leaves have a long history of use in traditional medicine in China and Russia and have demonstrated *invitro* activity against tumor necrosis factor-α, inhibition of pro-inflammatory cytokines, and enhancement of intestinal mucosal integrity (Ma et al., 2023). *Morus* species also present significant opportunities beyond fruit utilization. Their roots have been traditionally used for managing diuresis, tonicity, and neuropathic conditions, while leaves are widely recognized for their antidiabetic and antioxidant properties (Batiha et al., 2023). Similarly, *Physalis peruviana* roots contain withanolides with promising nutraceutical potential, and experimental studies have shown that β-hydroxywithanolide E accumulation in cape gooseberry roots can be stimulated by elicitors such as salicylic acid (Piñeros-Castro et al., 2009; Tarun and Biswajit, 2023).

9 Quality of evidence and future research needs

Despite the growing number of studies reporting beneficial biological effects of underutilized berry species, the overall quality

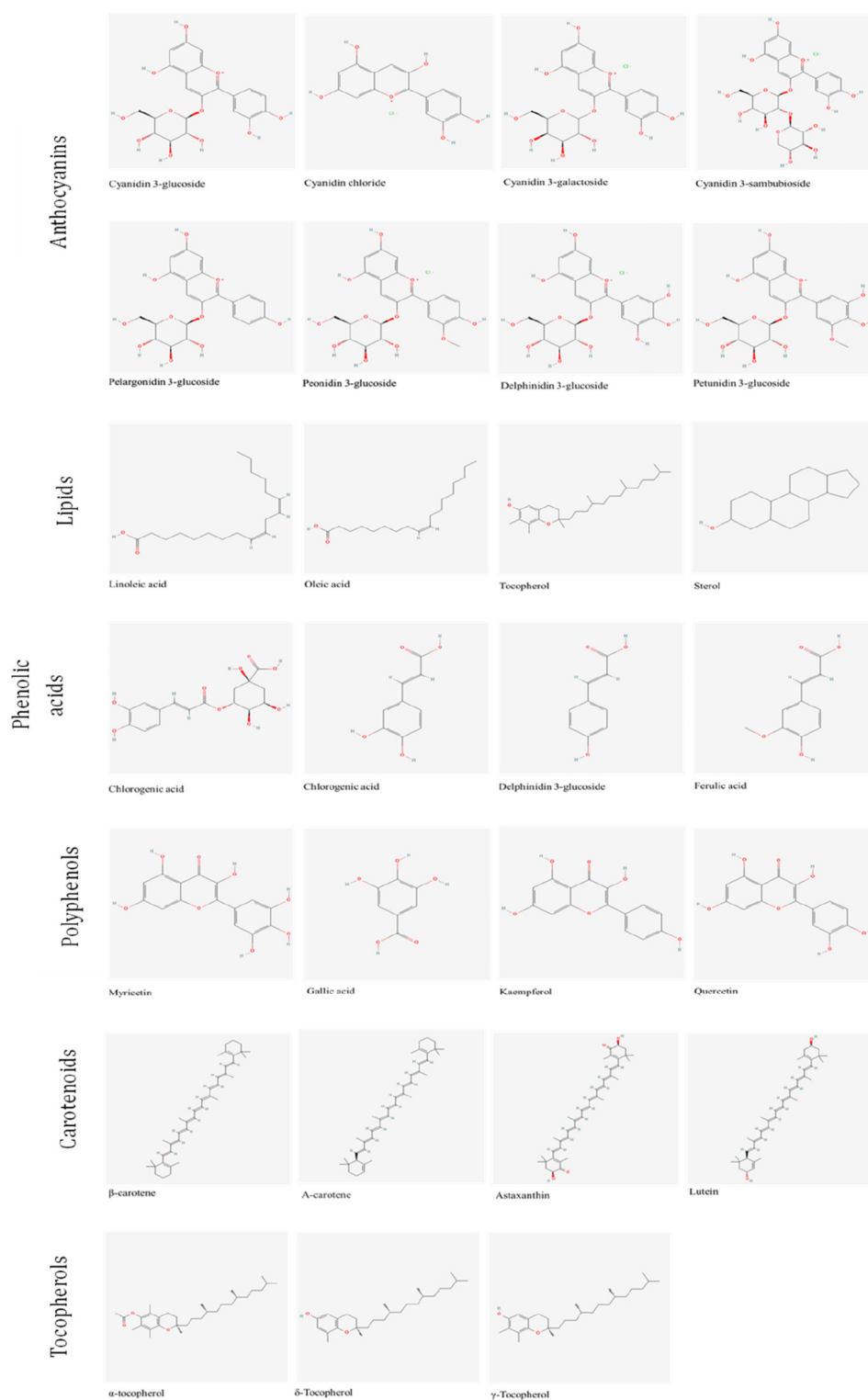


FIGURE 3
Representative chemical structures of major bioactive classes reported in underutilized berry species, including anthocyanins, phenolic acids, polyphenols, carotenoids, and lipid-derived compounds.

and strength of evidence remain uneven. Most available data are derived from *invitro* assays and animal models, whereas well-designed human clinical trials are still limited. Furthermore, variations in plant part used,

extraction methods, dosage, and experimental models complicate direct comparison across studies and may partly explain differences in reported outcomes. In several cases, biological effects observed under controlled

TABLE 6 Experimentally reported biological effects of selected underutilized berry species.

Species	Plant part	Concentration	Model type	Main observed effect	References
<i>Ribes nigrum</i>	Fruit (anthocyanin extract)	150 mg kg ⁻¹ body weight day ⁻¹ (oral gavage)	HFD-induced obesity model in C57BL/6 J mice	Reduced body weight gain and hyperlipidemia, alleviation of hepatic steatosis through improved hepatic lipid metabolism, along with modulation of gut microbiota, particularly <i>Akkermansia muciniphila</i>	Song et al. (2021)
<i>Ribes</i> spp.	Fruit	—	<i>Invitro</i> antioxidant and phytochemical profiling	High polyphenol content and strong antioxidant capacity; red currant exhibited higher ABTS and FRAP activity compared with black and white currants	Kierońska et al. (2024)
<i>Aronia</i> spp.	Fruit (freeze-dried powder)	820–900 mg GAE 100 g ⁻¹	Food formulation (bakery and confectionery products)	High polyphenol retention, enhanced antioxidant activity, and improved stability of anthocyanins during processing	Sadowska et al. (2021)
<i>Aronia melanocarpa</i>	Pomace	—	Extraction process (PLE; MAE + cryogrinding)	High recovery of polyphenols and anthocyanins from pomace; improved preservation of heat-sensitive compounds, efficient waste valorization, and rapid achievement of high-concentration functional extracts	Repajić et al. (2025)
<i>Aronia</i> spp.	Leaves	—	Food system (meat products)	Reduced lipid oxidation (TBARS ↓42%), improved shelf-life and sensory quality during storage	Kuzmanović Nedeljković et al. (2023)
<i>Hippophae rhamnoides</i>	Flavonoid-enriched fruit extract	100–300 mg kg ⁻¹	<i>Invivo</i> (HFD-induced obese mouse model)	Dose-dependent reduction of serum and liver triglyceride levels	Yang et al. (2017)
<i>Hippophae rhamnoides</i>	Fruit extract	100 mg kg ⁻¹ body weight	<i>Invivo</i> (hyperlipidemic rats)	Reduced oxidative damage associated with lipid peroxidation	Cho et al. (2017)
<i>Hippophae rhamnoides</i>	Seed oil	500 mg mL ⁻¹	<i>Invitro</i> (UV-induced human skin cells)	Reduced ROS generation by ~25%	Gęgotek et al. (2018)
<i>Hippophae rhamnoides</i>	Leaf extract	5–20 µg mL ⁻¹	<i>Invitro</i> (PC-12 cells)	Decreased proportion of apoptotic PC-12 cells	Serban et al. (2019)
<i>Hippophae rhamnoides</i>	Leaf aqueous extract	3.12–50 µg mL ⁻¹	<i>Invitro</i> (LNCaP and C4-2 prostate cancer cells)	Inhibition of cancer cell proliferation and migration	Masoodi et al. (2020)
<i>Hippophae rhamnoides</i>	Polyphenol extract	80–120 µg mL ⁻¹	<i>Invitro</i> (human colon cancer cells)	Downregulation of cyclin expression and reduced cell proliferation	Wu G. et al. (2021)
<i>Hippophae rhamnoides</i>	Fruit (phenolic fraction)	0.5–50 µg mL ⁻¹	<i>Invitro</i> (human plasma or blood platelets)	Reduced plasma lipid peroxidation and protein carbonylation; ~60% inhibition of lipid peroxidation at 50 µg/mL	Mohamed et al. (2020)
<i>Lonicera caerulea</i>	Berry extract	250 g L ⁻¹	<i>Invivo</i> (high-fat diet mouse model)	Suppressed obesity-related outcomes, reduced fat deposition, improved insulin sensitivity, and decreased oxidative stress	Del-Chierico et al. (2017)
<i>Lonicera caerulea</i>	Berry extract	250 g L ⁻¹	<i>Invivo</i> (high-fat diet-induced NAFLD mouse model)	Attenuation of NAFLD progression through modulation of gut microbiota and reduction of hepatic steatosis	Wu et al. (2018)
<i>Lonicera caerulea</i>	Fruit aqueous extract	100–400 mg kg ⁻¹	<i>Invivo</i> (HFD-induced mouse model)	Reduced lipid peroxidation (↓MDA), decreased oxidative stress markers, and normalization of endogenous antioxidant defense system	Chun et al. (2018)

(Continued)

TABLE 6 Continued

Species	Plant part	Concentration	Model type	Main observed effect	References
<i>Lonicera caerulea</i>	Fruit (anthocyanin-rich extract)	400 mg anthocyanins	Human intervention (double-blind, counter-balanced crossover study)	Improved episodic memory and reduced blood pressure following acute supplementation	Bell and Williams, (2019)
<i>Lonicera caerulea</i>	Fruit (dry fruit extract)	—	<i>Invivo</i> (male obese fa/fa zucker rats)	Increased SOD expression; reduced NADPH oxidase activity and lipid peroxidation; improved lipid profile and enhanced vascular nitric oxide synthase (NOS) activity	Dayar et al. (2021)
<i>Sambucus nigra</i>	Berry (anthocyanins)	272.9 mg 100 g ⁻¹ FW	<i>Invitro</i> (DPPH assay; LC-MS characterization)	High anthocyanin content correlated with strong antioxidant activity and detailed polyphenol characterization	Anton et al. (2013)
<i>Sambucus nigra</i>	Elderberry juice	0.15–1.53 mg mL ⁻¹	Analytical (UPLC–MS/MS)	Comprehensive identification and quantification of anthocyanins and total polyphenols in commercial elderberry juices	Wu et al. (2013)
<i>Sambucus nigra</i>	Berry (anthocyanins)	48.5 mg 100 g ⁻¹ DW	Analytical (LC–MS/IT-TOF)	Accurate identification and quantification of major anthocyanins, supporting standardization of elderberry-derived antioxidant products	Fejér et al. (2013)
<i>Morus alba</i>	Leaf (ethanol extract)	250–750 mg kg ⁻¹ body weight	<i>Invivo</i> (type II diabetic rat model)	Significant reduction in fasting and non-fasting blood glucose levels through regeneration of pancreatic β -cells, demonstrating anti-diabetic activity	Hunyadi et al. (2012)
<i>Morus alba</i>	Fruit (70% ethanol extract)	400 μ g mL ⁻¹	<i>Invitro</i> (H ₂ O ₂ -induced oxidative injury in pancreatic MIN6N β -cells)	Significant protection against oxidative injury and improved β -cell viability under oxidative stress conditions	Yan and Zheng, (2017)
<i>Morus alba</i>	Root bark (flavonoid: Leachianone G)	—	<i>Invitro</i> (HSV-1-infected cell model)	Inhibited herpes simplex virus type-1 (HSV-1) replication, demonstrating antiviral activity of root bark-derived flavonoids	Zafar et al. (2013)
<i>Morus nigra</i>	Fruit (mulberry juice; cyanidin-3-glucoside)	10–15 mL kg ⁻¹ day ⁻¹ for 1 week (137 mg 100 g ⁻¹ anthocyanins)	<i>Invivo</i> (MPTP-induced Parkinson's disease model in male BALB/c mice)	Attenuated levodopa-induced dyskinesia (LID) in MPTP-induced Parkinson's disease	Fahimi and Jahromy, (2018)
<i>Vaccinium vitis-idaea</i>	Fruit (wild berries)	Phenolics: 477–775 mg 100 g ⁻¹ FW; anthocyanins: 20–57 mg 100 g ⁻¹ FW; proanthocyanidins: 141–269 mg 100 g ⁻¹ FW	<i>Invitro</i> (ABTS +, FRAP antioxidant assays)	High antioxidant capacity and rich phenolic composition; biochemical and physicochemical profiles significantly influenced by geographical origin, supporting potential for functional food and nutraceutical development	Urbonavičienė et al. (2023)
<i>Vaccinium vitis-idaea</i>	Fruit (freeze-dried extract)	1–5 mg mL ⁻¹	<i>Invitro</i> (3T3-L1 adipocytes)	Decreased ROS production and NOX4 expression; increased antioxidant enzymes (SOD2, GPx, catalase), indicating strong antioxidant activity	Kowalska et al. (2019)
<i>Vaccinium vitis-idaea</i>	Fruit (anthocyanin and non-anthocyanin polyphenol fractions)	5–20 μ g mL ⁻¹	<i>Invitro</i> (3T3-L1 adipocytes)	Reduced lipid accumulation and triglyceride content; downregulation of adipogenic and lipogenic markers (aP2, FAS, DGAT1), indicating anti-adipogenic activity	Kowalska et al. (2021)
<i>Lycium barbarum</i>	Seeds	35.75–46.16 mg 100 g ⁻¹ carotenoids (method-dependent)	Extraction study (SFE-CO ₂ , USE, SE)	High recovery of carotenoids from seeds, indicating strong potential for nutraceutical and functional food applications	Liu et al. (2019)

(Continued)

TABLE 6 Continued

Species	Plant part	Concentration	Model type	Main observed effect	References
<i>Lycium barbarum</i>	Seeds	671–894 mg 100 g ⁻¹ stigmasterol (method-dependent)	Extraction study (SFE-CO ₂ , USE, SE)	Efficient extraction of stigmasterol, supporting seed oil valorization for nutritional and pharmaceutical uses	Zhang Y. et al. (2022)
<i>Cornus mas</i>	Water extract of <i>Cornus mas</i> fruits (Serbia)	750 µg mL ⁻¹	Colorimetric assay (MCF-7 cells)	Inhibited proliferation of MCF-7 breast cancer cells	Forman et al. (2015)
<i>Cornus mas</i>	Gold nanoparticles synthesized using <i>C. mas</i> extract (AuNPs-CM)	>20 µg mL ⁻¹	Cell titer blue assay (HaCaT, A431 cells)	The cytotoxic effect became significant at concentrations above 20 µg mL ⁻¹ . Notably, a stronger cytotoxic response was observed in HaCaT cells compared with A431 cells, which is consistent with the higher cellular uptake recorded in HaCaT cells after 24 h of incubation. The half-maximal inhibitory concentrations (IC ₅₀) were 23.9 µg/mL for HaCaT cells and 28.19 µg mL ⁻¹ for A431 cells	Perde-Schrepler et al. (2016)
<i>Cornus mas</i>	AuNPs, AgNPs, and water extract of <i>Cornus mas</i> fruits	Up to 50 µg mL ⁻¹	Colorimetric assay HGF and DOK cell lines	AuNPs stimulated HGF cell proliferation in a dose-dependent manner up to 50 µg mL ⁻¹ , after which viability declined. In DOK cells, AuNPs, AgNPs, and fruit extract caused a dose-dependent reduction in viability; AuNPs showed the highest cytotoxicity, with reduced viability observed from 10 µg mL ⁻¹	Baldea et al. (2020)
<i>Physalis peruviana</i>	Fruit (hydroethanolic extract; 80% ethanol)	–	Human colorectal adenocarcinoma (Caco-2) and non-small-cell lung carcinoma (NCI-H460) cells	Identified physalin derivatives and withanolides; extract showed significant antiproliferative activity against both cancer cell lines	Añibarro-Ortega et al. (2025)
<i>Physalis peruviana</i>	Calyx (hydroethanolic and aqueous extracts)	—	Cell-based antioxidant and inflammatory assays	High antioxidant activity; inhibition of advanced glycation end products (AGEs) formation and nitric oxide production; antiproliferative effects	Añibarro-Ortega et al. (2025)
<i>Amelanchier</i> spp.	Fruits (methanolic extract)	5.0 mmol TE 100 g ⁻¹ fruit	Invitro antioxidant assays (DPPH, FRAP)	Strong free-radical scavenging activity and ferric-ion reducing capacity	Juríková et al. (2013); Lachowicz et al. (2017)
<i>Amelanchier</i> spp.	Fruits (ethanolic extract)	0.35 ± 0.02 mg mL ⁻¹ (IC ₅₀)	Lipid peroxidation inhibition assay	Inhibition of lipid peroxidation, indicating anti-atherosclerotic potential	Sagandiyk et al. (2024)
<i>Amelanchier</i> spp.	Fruits (polyphenol-rich extract)	1 µg mL ⁻¹	RAW 264.7 macrophages	Suppression of nitric oxide production <i>via</i> inhibition of iNOS and COX-2 expression	Juríková et al. (2013)
<i>Amelanchier</i> spp.	Fruits (extract)	100 µg mL ⁻¹	HepG2 cell cytoprotection model	Protection against tert-butyl hydroperoxide-induced oxidative cellular damage	Gunawardana et al. (2016)

laboratory conditions have not yet been validated under physiological or clinical settings, highlighting the need for standardized methodologies and long-term intervention studies to confirm efficacy and safety.

10 Conclusion

Underutilized berry species represent a valuable yet largely untapped resource for enhancing nutritional quality, climate

resilience, and diversification of horticultural production systems. The present review reveals that many of these berries are particularly rich in bioactive compounds such as polyphenols, anthocyanins, carotenoids, polysaccharides, and bioactive lipids, which largely explain their strong antioxidant and health-promoting effects. In addition, several species show a high degree of tolerance to abiotic stresses, including drought, salinity, and low soil fertility, supporting their suitability for cultivation in marginal environments. Beyond

compositional attributes, the literature also points to increasing opportunities for value-added processing and commercialization, especially in functional foods, nutraceuticals, and ingredient-oriented supply chains. Nevertheless, wider adoption remains constrained by limited cultivar development, fragmented postharvest infrastructure, regulatory frameworks, and insufficient clinical validation. Targeted advances in breeding, processing standardization, regulatory alignment, and translational research will therefore be critical to facilitate scale-up and successful market integration.

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Conflict of interest

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