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Review

Bilberries vs. Blueberries: A Comprehensive Review

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Abstract: The genus *Vaccinium*, which includes approximately 450 species, features economically significant berries such as bilberries (*Vaccinium myrtillus*) and blueberries (*Vaccinium corymbosum*). Bilberries flourish in acidic, well-drained soils, typically found in heathlands and coniferous forests, while blueberries benefit from a broader range of soil types and intensive agricultural practices. Sustainable cultivation strategies, including organic fertilization and efficient water management, are vital for optimizing production and addressing the environmental challenges posed by climate change. Both berries are rich in antioxidants and other nutrients, driving consumer interest and market growth despite competition from alternative crops. Additionally, tailored fertilization techniques are crucial for maximizing yield and fruit quality. By implementing circular economy principles, the production of bilberries and blueberries can enhance sustainability and profitability, ensuring their long-term success in agricultural systems.

Keywords: bilberry; blueberry; acidic soils; anthocyanins; acidic soil; climate change; market potential

1. Introduction

The genus *Vaccinium*, part of the Ericaceae family, includes around 450 species of terrestrial shrubs found mainly in the Northern Hemisphere, as well as in tropical mountain regions of Asia, Central, and South America. A few species are also native to Africa, Madagascar, and China, where 92 species (51 endemic) are found. High densities of *Vaccinium* occur in the Himalayas, New Guinea, and the Andes. Southeast Asia is home to nearly 40% of these species, while around 35% are native to the Americas. Among them, *Vaccinium uliginosum* is one of the most widely distributed species [1]. In Europe, the wild *Vaccinium* species include *V. myrtillus* L. (bilberry), *V. vitis-idaea* L. (lingonberry), *V. oxycoccus* L. (cranberry), and *V. uliginosum* L. (bog bilberry). The most economically significant cultivated species of the genus belong to the subfamily Vaccinioideae, with the key representatives being cranberry, blueberry, huckleberry, and bilberry, which dominate global fruit production in this group [2].

The genus *Vaccinium* is complex, with traditional classifications often failing to distinguish species due to overlapping characteristics. Many tropical species are understudied but hold potential for fruit and ornamental uses. Cytologically, *Vaccinium* species exhibit polyploidy, which complicates species identification, particularly in blueberries where hybridization is common. Germplasm resources are crucial, with major collections maintained at research institutions to preserve genetic diversity for breeding and conservation efforts [1].

In agronomy and agriculture, the significance of *Vaccinium* species is noteworthy, as they contribute substantially to economic, nutritional, and ecological dimensions. High-value crops such as blueberries (*Vaccinium corymbosum*), cranberries (*Vaccinium macrocarpon*), and bilberries (*Vaccinium myrtillus*) play a crucial role in global agricultural markets. The commercial production of these fruits not only bolsters local economies but also offers farmers avenues for diversification and income generation [3]. Furthermore, cultivating these berry species promotes agricultural biodiversity by preserving essential genetic resources critical for breeding programs. This genetic diversity enhances resilience against pests, diseases, and climate change, ultimately supporting food security. As perennial plants, they play a vital role in improving soil health [4]. Their root systems contribute to soil stabilization and erosion control, while the organic matter from decaying plant material enhances soil structure and fertility [5]. Additionally, these plants provide habitat and food sources for various pollinators and wildlife, thereby supporting overall ecosystem integrity [6].

Sustainable cultivation of *Vaccinium* species emphasizes practices that enhance productivity while reducing environmental impact. Key strategies include soil management techniques like cover cropping and mulching, which improve soil health and prevent erosion [7]. Integrated Pest Management (IPM) combines biological controls and cultural practices to manage pests with minimal chemical use [8]. Efficient water management through drip irrigation and rainwater harvesting optimizes water use [9], while organic farming practices reduce reliance on synthetic chemicals [10]. Additionally, crop rotation enhances soil fertility and breaks pest cycles [11], and protecting surrounding habitats supports vital ecosystem services like pollination [12]. Collectively, these practices foster environmental health and ensure the long-term viability of berry farming.

The market potential for *Vaccinium* species, particularly blueberries, cranberries, and bilberries, is significant due to rising consumer demand for their health benefits and antioxidant properties, attributed to their rich chemical composition, including vitamins, minerals, and phenolic compounds like anthocyanins. This expanding global market offers lucrative opportunities for growers, as these berries gain popularity in various food products [2].

However, challenges such as climate change may impact yields and quality, requiring growers to adopt resilient practices and invest in improved varieties [13,14]. Additionally, competition from other berry crops can pressure prices, highlighting the need for efficiency and value-added product development [15]. Continued investment in research and sustainable practices will be essential for maintaining profitability and ensuring the long-term success of *Vaccinium* cultivation in the evolving agricultural landscape.

The purpose of this study is to provide a comprehensive analysis of the genus *Vaccinium*, focusing on both bilberry (*Vaccinium myrtillus*) and blueberry (*Vaccinium corymbosum*). *V. myrtillus*, known for its unique ecological, nutritional, and economic value, will receive primary attention; however, comparisons with *V. corymbosum* will highlight key differences and similarities between these two species. This study will explore the botanical characteristics, ecological and agronomic requirements, and growth conditions of bilberries and blueberries. We will also examine pest and disease management, harvesting practices, post-harvest handling, and sustainable approaches relevant to both species, alongside an analysis of their chemical compositions. Finally, the economic viability, market potential, and future prospects of both *V. myrtillus* and *V. corymbosum* will be evaluated, considering ongoing challenges and opportunities in their cultivation and commercialization.

2. Botanical Description and Distribution

Vaccinium myrtillus, commonly known as bilberry, is a low-growing shrub native to northern Europe, now also present in parts of North America and Asia [16]. This species, also referred to as European blueberry, whortleberry, and blaeberry, belongs to the large *Vaccinium* genus, which includes other well-known berries like blueberry (*Vaccinium corymbosum*) and cranberry (*Vaccinium macrocarpon*). While bilberries and blueberries are often mistaken for one another due to their similar appearance, true blueberries are native to the United States [17].

Vaccinium myrtillus (bilberry) is a perennial, low-growing shrub that typically reaches a height of 35 to 60 centimeters. Bilberry plants typically thrive in heathlands, meadows, and moist coniferous forests, favoring moderate shade and moderately humid conditions. They are well-adapted to acidic soils, including organic forest soils, mountainous mineral heaths, and old peat bogs, particularly in central and northern Europe. [2,17].

Two subspecies of bilberry, *V. myrtillus ssp. myrtillus* and *V. myrtillus ssp. oreophilum* (Rydb.) Dorn, have been identified based on morphological differences, though there is no consensus on their formal recognition. Bilberries are typically diploid, but polyploid variants have been found in North America. The berries are bluish-black, globose, with purple pigmented flesh and brownish-red seeds, sometimes covered by a gray bloom. Flowering occurs in early spring as leaves emerge, making the plant susceptible to weather fluctuations. Cold spells during this time can reduce pollinator activity, particularly bees and flies, while frost can damage blooms and affect berry development. Unlike other *Vaccinium* species, bilberry flowers are solitary or paired, with fruit development taking 8–10 weeks. During the 2–3 weeks ripening phase, anthocyanin pigments rapidly accumulate, along with flavor compounds and aromatic volatiles [18,19]. The plant produces spheroidal blue or black fruits, which are intensely colored and measure between 5 to 9 millimeters in diameter. The pulp shares the same dark hue as the peel, offering a sweet flavor with astringent notes [20].

In 1911, a collaborative effort to domesticate the highbush blueberry began between Elizabeth C. White of the J. J. White Company in Whitesbog, New Jersey, and Frederick V. Coville from the U.S. Department of Agriculture. Their swift selection and evaluation process centered on three primary factors: identifying superior wild germplasm with the help of local pickers, creating progeny through systematic crossbreeding, and employing various methods for clonal propagation. The launch of the first domesticated blueberry crop in 1916 marked a notable improvement in blueberry quality and paved the way for the modern blueberry industry [21].

When it comes to blueberries, their versatility and economic value are notable. These berries, as members of the *Vaccinium* genus and *Cyanococcus* subgenus, include a range of types such as wild lowbush (*V. angustifolium*) and cultivated highbush species like *V. corymbosum L.* and *V. virgatum Ait.* (rabbiteye) [1]. Highbush varieties are cultivated worldwide, notably in the U.S., Canada, Europe, and New Zealand [22], while rabbiteye types are regionally suited to the southeastern U.S., and lowbush blueberries flourish in northeastern North America [23]. With a flowering phase in early spring, blueberry fruits develop in phases, transitioning from green to blue over about 40–60 days [19].

3. Agronomic Requirements

Bilberries, being wild and naturally adapted to boreal and temperate forest ecosystems, have specific agronomic requirements for optimal growth and productivity [24,25]. Successful cultivation of bilberries involves carefully managing soil conditions, climate, water availability, and nutrient levels to replicate the natural environments in which they thrive [26,27]. Meeting these agronomic needs is crucial for maintaining plant health and maximizing berry yield, especially as interest in commercial bilberry cultivation grows.

Bilberries thrive in acidic soils, typically found in forested regions rich in organic matter. The ideal soil for bilberries is well-drained, loamy, and highly acidic, with a pH between 4.0 and 5.5. These conditions promote effective root function and nutrient uptake, which are vital for healthy growth and fruit production [28,29]. Organic materials like peat and decomposing leaves help retain moisture while providing slow-release nutrients [30]. However, excessive moisture or poor drainage can lead to root rot, highlighting the importance of maintaining appropriate soil structure and drainage in cultivation [31]. When it comes to specific soil requirements for cultivating highbush blueberry (*Vaccinium corymbosum L.*), the soil must have a low pH of 4.2 to 5.5 to ensure optimal nutrient availability [32]. It should also be rich in organic matter, ideally containing 7 to 10%, which aids in moisture retention and provides essential nutrients [33,34]. Good aeration is crucial, as blueberries have shallow, highly branched root systems that are sensitive to waterlogged conditions. Therefore, well-drained soil is necessary to prevent root rot and other diseases. Additionally, incorporating organic materials like peat, sawdust, and bark enhances soil structure and promotes healthy root development, contributing to successful blueberry production [35].

Bilberry roots predominantly inhabit the organic top layer, while subsoil layers also play a role in nutrient supply. High sand and gravel content can impede growth during dry periods due to reduced water retention [36–38]. Nutrient availability in mineral soils is often low, particularly for essential elements like phosphorus, potassium, magnesium, and calcium. Yet, bilberries benefit from associations with ericoid mycorrhiza, which enhance nutrient uptake, particularly phosphorus, making them suitable for nutrient-poor conditions [39,40].

The growth of bilberries also influences soil microbial communities, shifting them toward mycorrhizal fungi and bacteria involved in cellulose degradation, which can lead to lower nitrogen availability and altered nutrient cycling [39]. While bilberries excel in acidic soils with a pH below 4.5, they struggle in alkaline conditions (above pH 6), which adversely affect growth and chlorophyll production [41].

Temperature plays a crucial role in the growth and development of bilberries. Soil warming can stimulate nitrogen cycling and enhance shrub growth, resulting in significant increases in shoot and leaf production—by 62% and 44%, respectively. However, even a slight increase of 2–3 °C in December can markedly reduce the frost hardiness of bilberries, leading to dehardening and triggering growth as early as mid-January when temperatures exceed 10 °C. For optimal development, bilberries require winter temperatures below 10 °C to achieve proper hardening [42–45]. However, unseasonably warm winter conditions can disrupt this process, causing delayed bud burst of up to one week and a staggering reduction in flowering by over 90% [45,46]. This is particularly concerning given that bilberries are sensitive to early spring frosts, which can occur as the flowers emerge during leafing. Such frost events can severely hinder pollination and the formation of berries, leading to reduced yields [39]. In comparison, the success of highbush blueberry production relies heavily on atmospheric conditions, particularly temperature and precipitation, during both the growing season and winter dormancy. Warm, dry summers can impede budding, while sudden winter temperature drops pose a risk of frost damage. Although Central and Eastern Europe generally offer a favorable climate for most blueberry varieties, it's essential to analyze specific climatic factors when establishing a plantation. Notably, minimum winter temperatures down to -25 °C usually do not harm blueberry shrubs; however, winter warming can disrupt the hardening process, increasing the risk of frost damage, especially to the sensitive flower buds. Understanding these climatic influences is vital for optimizing cultivation practices and ensuring healthy yields [47].

Blueberry cultivars can be categorized based on their chilling requirements: high, moderate, and low. Chilling conditions, essential for flowering initiation after winter, significantly influence the growth of perennial plants [48]. Historically, blueberries thrived in northern regions of the United States, where favorable edaphoclimatic conditions, including a pH of 4.8 and temperatures between 0–7°C, supported their growth [49]. However, increasing temperatures, drought, and adverse weather events pose serious challenges to blueberry production. Drought can lead to reduced yields, while elevated temperatures adversely affect pollination and fruit development [50]. High atmospheric UV levels further compromise production and fruit quality. Interspecific hybridizations with wild southern lowbush species have resulted in varieties that can tolerate a wider range of climates, helping to maintain yield and fruit quality. The rising global temperatures over recent decades may have facilitated the adaptation of these cultivars to higher temperature stress during fruit development, which is crucial for sustaining and increasing blueberry production worldwide [50].

Elevation gradients are a valuable framework for examining the impact of climate on vegetation, as temperature generally decreases by approximately 5.5 °C per kilometer of elevation. This decline influences various ecosystem properties, including plant diversity and productivity [51,52]. Although species richness typically decreases with elevation, some studies have identified a mid-elevation peak, particularly around tree lines where environmental stress and competition are moderate. For bilberry, growth traits such as ramet height, age, and xylem ring width are negatively correlated with elevation, indicating that higher altitudes yield shorter and younger plants with thinner growth rings. While elevation affects these growth traits, it does not appear to directly influence overall shrub cover; rather, cover is positively associated with bilberry growth, suggesting that this key species may shape plant community dynamics. The lack of a direct relationship between elevation and shrub cover indicates that other ecological factors, such as soil conditions or historical land use, might play significant roles [53]. In all, the regeneration of bilberry is not only important for the survival of itself but contributes to the maintenance of plant diversity in its alpine habitat and points toward its keystone status in these environments.

Bilberries (*Vaccinium myrtillus*) thrive in moist, well-drained soils, making adequate water availability crucial for their growth and fruit production [54]. These plants prefer environments where moisture levels are consistently maintained, as excessive drought can lead to reduced fruit set and poor berry quality. While bilberries are somewhat drought-tolerant, prolonged dry periods can stress the plants, adversely affecting their health and yield [55].

Chemical fertilizers, primarily nitrogen (N) and potassium (K), are widely used to boost crop yields, including blueberries. These macronutrients are vital for photosynthesis and the transport of its products. Imbalances in their levels can disrupt assimilation processes, affecting sugar metabolism and carbon assimilation. This review explores the mechanisms of K and N uptake in blueberry roots and their roles in enhancing photosynthetic efficiency [56]. The study by Fang et al., 2020 investigated the nitrogen (N) requirements of young southern highbush blueberry (SHB) plants, specifically focusing on optimizing fertigated N rates for growth and yield. Conducted with one-year-old 'Emerald' and 'Farthing' cultivars, the research evaluated the effects of varying annual N application rates (0, 42, 84, 168, and 336 kg N ha^{-1}) through drip irrigation. The findings revealed that while higher N rates improved indicators such as bloom timing, canopy ground cover, and overall fruit yield, they also negatively impacted berry size and weight. Notably, the highest N rate presented a significant risk of nitrate leaching. The study concluded that maximum fruit yields were achieved at annual N rates of 222 kg ha^{-1} for 'Emerald' and 206 kg ha^{-1} for 'Farthing,' emphasizing the need for careful nutrient management in blueberry cultivation to balance growth and environmental concerns [57].

Similarly to blueberries, nitrogen supply significantly influences bilberry growth, boosting both root and shoot development. Increased nitrogen leads to higher plant dry weight, more leaf production, and larger leaf area, with roots and woody stems being the main nitrogen storage organs [58,59]. The first growth flush relies heavily on nitrogen remobilization, supplying most of the nitrogen needed for new leaf growth [60]. Bilberry quickly reallocates nitrogen to adapt to fluctuating nitrogen availability in its environment. High nitrogen levels also raise leaf nitrogen concentration, increasing light-harvesting compounds like chlorophyll. However, nitrogen alone may not drastically change plant communities unless combined with additional atmospheric inputs. Phosphorus also supports bilberry growth by enhancing root development and fruit formation, but its availability is limited in acidic soils [39]. On the other hand, potassium is often provided through decaying mulches, but additional supplementation should be based on soil or tissue testing. If needed, potassium can be applied using mineral forms like sulfate-of-potash-magnesia, granite meal, or greensand, with some forms suitable for organic production. High-quality compost can serve as an excellent all-around fertilizer for blueberries, and depending on soil conditions, may fulfill all nutrient needs. Aged animal manure is sometimes used but is less common. Since blueberry roots are not extensive, fertilizers should be applied under the plant canopy to reach the roots. Some

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organic growers also use foliar feeding, typically with seaweed and fish emulsion, especially when plants are stressed [28].

4. Harvesting Process of Bilberries and Blueberries

Harvesting wild plants is a traditional practice that can remain sustainable if plant populations are allowed to reproduce and persist. However, due to their fixed locations, wild plant populations cannot avoid the repeated impact of harvesting, which can pose risks if sensitivity is overlooked. Harvesting effects vary depending on practices such as intensity, the plant parts collected, tools used, and the plant's life cycle and demographic traits, as well as the ecological niche where it grows. To ensure sustainability, an integrative approach is essential, combining ecological variables with the sociocultural aspects of harvesting [61].

The collection of wild plants, practiced since ancient times, remains a significant connection to nature, even in heavily developed areas like Europe. Originally essential for meeting basic needs such as food and medicine, this practice now continues for diverse reasons, with cultural ties being especially prominent. Wild plants fulfill a wide range of uses—from food and medicine to materials, fuel and ornamentation. These plants represent valuable ecosystem services, with each specific use offering unique benefits that enrich human culture and well-being [62].

The harvest of bilberries (*Vaccinium myrtillus*), which is a wild shrub [63], involves careful timing [64], methods [65], and environmental consideration [66] to maintain both the berry's quality and the integrity of its natural habitat. Growing in acidic soils in forests and highland regions [67] bilberries are generally gathered between July and August, timed to their full ripeness to ensure optimal flavor and nutritional value [68]. Bilberry harvesting is predominantly done by hand, a labor-intensive process that remains favored for berries often harvested for direct consumption. Despite the effort involved, hand harvesting is popular due to its effectiveness in ensuring high-quality fruit while minimizing damage to the plants [69].

Bilberry-rich areas can be difficult to access, as they grow in remote, forested regions or high-altitude landscapes [70,71]. Their environment requires sustainable harvesting practices to prevent habitat degradation and ensure continued fruit production for future years [72].

Bilberry harvesting is a cherished tradition in Estonia, serving as both a source of sustenance and a vital cultural practice. As a significant non-timber forest product, bilberries contribute to local economies, particularly in rural and underemployed regions, with estimates suggesting that 30% to 50% of the annual yield is collected for commercial sale and personal consumption. The preferences and behaviors of bilberry pickers are shaped by ecological conditions, forest management practices, and the socio-cultural context of local communities. Study of Remm et al., 2018 investigated the relationship between natural bilberry supply and harvesting practices in Estonia through interviews and geographic information system analyses, focusing on the factors that define optimal harvesting sites, picker responses to forest management, and their adaptability to landscape changes. The findings highlighted the importance of maintaining a stable network of berry-picking sites and emphasize the need for effective spatial planning and information sharing to support sustainable bilberry harvesting [73].

Furthermore, wild berry picking, particularly of bilberries (*Vaccinium myrtillus*) and lingonberries (*Vaccinium vitis-idaea*), is also a long-standing tradition in Finland that combines leisure and economic benefits. Study of Manninen & Peltola, 2013 investigated the effects of different harvesting methods—specifically plastic hand rakes and long-handed metal rakes—on berry production. Through a factorial experiment, the research aimed to determine how various picking techniques influence the quantity of berries produced. The results demonstrated that even the more aggressive harvesting method, using powerful metal rakes, did not significantly impact berry yields. This suggests that, when applied judiciously, these harvesting practices can be sustainable and support the ecological integrity of wild berry populations. Understanding the implications of different harvesting techniques is crucial for ensuring that the cultural and economic importance of wild berry picking can continue without compromising the health of these vital ecosystems [74].

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In contrast to bilberries, which are primarily harvested by hand and often involve lower labor demands due to their wild growth and limited commercial production, blueberries require significant seasonal labor, especially during the harvesting period. This phase accounts for up to 90% of the total labor needs in blueberry cultivation, with producers facing high costs due to the intensive labor involved—up to 1,500 hours per hectare per year. The reliance on manual labor for blueberries presents challenges in securing sufficient workers, which has led to income losses for some producers during peak harvest times. To address these issues, there is a growing interest in mechanizing the harvesting process for blueberries, which could reduce labor costs, improve productivity, and help mitigate labor shortages during critical periods [75].

Study of Brondino et al., 2021 provided preliminary findings on mechanical blueberry harvesting of the "Cargo®" cultivar in Italy's Piedmont region. Comparing a prototype machine and the Easy Harvester® to manual picking, the research noted significant cost reductions, with the prototype reducing costs by 39% and the Easy Harvester® by about 50%. However, transitioning to mechanical harvesting required changes in farming practices and emphasized the need for continued research in the industry [75]. The same group of researchers evaluated the quality of two blueberry cultivars, Cargo® and Top Shelf®, in relation to mechanical harvesting and short-term storage (up to 28 days). The researchers compared mechanically harvested samples with those harvested by hand over two years. In the first phase, a laboratory simulation assessed the cultivars' response to mechanical harvesting, revealing a higher percentage of shriveled berries in mechanically harvested samples due to low pruin/surface wax content at harvest. In the second phase, berries were stored at 2 ± 1 °C and 90% relative humidity for 28 days. Despite some quality differences, all samples remained marketable after storage, with Total Soluble Solids Content (TSSC) higher in the mechanically harvested group. Overall, the automation of harvesting did not significantly impact blueberry quality post-storage [76].

Table 1 presents a comprehensive comparison of manual and mechanical blueberry harvesting, outlining the key advantages and disadvantages of each method. This comparison serves to illustrate the trade-offs involved in choosing a harvesting technique, considering factors such as labor costs, fruit quality, and operational efficiency.

Table 1. Comparison of manual vs. mechanical blueberry harvesting.

Aspect	Manual Harvesting	Mechanical Harvesting
Pros	Higher fruit quality and lower damage	Significant labor cost reduction
	Greater selectivity in fruit picking	Increased harvesting efficiency
	Ability to harvest in diverse conditions	Faster harvest time
	Minimal need for specialized equipment	Potential for reduced dependency on seasonal labor
Cons	High labor costs	Potential for increased fruit damage
	Time consuming process	Lower fruit quality, especially for fresh market
	Labor availability issues	Requires investment in machinery
	Limited harvesting speed	May require adaptation on farming practices

5. Climate Change Effects on Bilberries

In recent decades, mounting evidence has highlighted the impacts of climate change on terrestrial ecosystems worldwide, with varying effects across different levels of ecological organization. High-latitude and high-elevation regions are particularly sensitive to these changes, experiencing more pronounced alterations in species distributions, community dynamics, and ecosystem functions [77].

Climate change significantly affects bilberry performance, as warming temperatures and rising atmospheric nitrogen levels may enhance the productivity of tundra plant communities. This shift can intensify competition among species, making the identity of neighboring plants more crucial for recruitment than overall species richness [39].

The study by Rohloff et al., 2015 examined the impact of climate on the nutritional quality of bilberries (*Vaccinium myrtillus*) across various regions in Norway. It was found that regional climate played a crucial role in determining bilberry quality, with temperature fluctuations significantly influencing phenolic and antioxidant levels. Higher average temperatures during the summer months in southern regions correlated with reduced total phenolics and antioxidants in the berries. The research also indicated that climatic factors such as precipitation and seasonal variations further affected berry composition, underscoring the potential for climate change to alter the nutritional profiles of bilberries in natural habitats [78].

Bilberry exhibits significant annual variability in berry production, closely tied to various climatic factors. Research of Selås et al., 2015 has identified critical climate variables, such as maximum temperatures in June, mean temperatures in August and September of the preceding year, snow depth in April, and minimum temperatures in May, that substantially influence berry yield. These climatic conditions are crucial for several key plant processes, including the timing of floral initiation, winter hardening, and frost injury avoidance during flowering. The species experiences a superficial state of winter dormancy, making it more susceptible to frost damage when there is insufficient snow cover. Moreover, increasing temperatures and changing precipitation patterns associated with climate change may exacerbate this vulnerability. As a result, the interplay between these climatic factors is essential for understanding the physiological mechanisms governing bilberry production. This relationship underscores the potential impacts of climate change on bilberry growth dynamics and berry yields, suggesting that shifts in climate patterns may lead to altered reproductive success and distribution of this species in the future. Addressing these changes will be vital for conservation efforts and sustainable management of bilberry habitats [79].

Climate change significantly affects blueberry cultivation, influencing various aspects of growth, yield, and quality. Altered precipitation patterns may cause water stress due to increased drought frequency or waterlogging from excessive rainfall, both of which negatively impact plant health [80]. Additionally, rising temperatures can extend the range and lifecycle of pests and diseases, increasing vulnerability and necessitating greater pesticide use [81]. These climatic shifts also affect fruit quality, altering the sugar-acid balance and potentially changing flavor profiles [82]. Phenological changes may disrupt flowering and fruiting times, leading to mismatches with pollinator activity and reduced fruit set [83]. Furthermore, growers may need to invest in irrigation systems to ensure adequate water supply, raising production costs [84].

Anthropogenic climate change threatens the nutritional quality of wild blueberries, a crop important for health and economy. In Maine, USA, warming has been linked to reduced fruit quality. A study assessed wild blueberries under three temperature conditions: active open-top heating (3.3 °C increase), passive heating (1.2 °C increase), and ambient control. Results showed decreases in total soluble solids, fructose, total soluble sugars, and total soluble protein with rising temperatures, while anthocyanin, total flavonoids, and phenolics remained unchanged. These findings suggest that future global warming may diminish the nutritional value and marketability of wild blueberries, emphasizing the need for mitigation strategies [85].

6. Differences Between Cultivated and Wild Bilberries

Consumers often prefer wild berries over cultivated ones due to their distinctive characteristics. Wild berries, including bilberries, tend to have a more intense, concentrated flavor and naturally lower sugar content compared to their cultivated counterparts, making them ideal for those seeking a tart, robust taste [86].

Wild bilberries (*Vaccinium myrtillus)* and cultivated blueberries (*Vaccinium spp.*) exhibit significant differences in their origin, genetic composition, and nutrient profiles. Bilberries grow exclusively in the wild, primarily in northern Europe, and maintain a consistent genetic makeup, resulting in higher antioxidant content, particularly anthocyanins, which are distributed throughout the fruit. In contrast, cultivated blueberries are derived from various species and have a diverse

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genetic background, leading to variations in chemical composition and antioxidant levels, with anthocyanins mainly located in the skin. This diversity affects flavor and texture, with wild bilberries generally offering a more intense taste and firmer structure. Additionally, the market for bilberries remains niche, emphasizing their uniqueness and potential for mislabeling or adulteration with cultivated blueberries, which are more widely produced and marketed [68].

Another study highlighted key differences between wild bilberries and cultivated blueberries in terms of their cuticular wax composition, which serves as a protective barrier against environmental stresses. Wild bilberries, exposed to more intense biotic and abiotic stresses, develop unique wax profiles distinct from those in cultivated berries like blueberries. Analysis of nine berry species from Northern Europe identified 59 wax compounds across categories like alkanes, alcohols, and fatty acids, with triterpenoids being notably abundant in blueberries (up to 62% of total wax). Wild bilberries, however, have unique compound concentrations, reflecting adaptations to natural stressors that differ from cultivated varieties bred for increased wax thickness and durability. This compositional variability underlines how environmental pressures shape wax profiles in wild versus cultivated berries and could inform selective breeding to enhance resistance and shelf-life in commercial berry production [87].

The differences in elemental composition between wild bilberries (*Vaccinium myrtillus*) and cultivated blueberries (*Vaccinium corymbosum*) were also studied, revealing significant implications for nutrition and health. Wild bilberries exhibit higher concentrations of essential minerals such as calcium, sodium, magnesium, manganese, and zinc, which are crucial for various physiological functions, including enzyme activity and immune support [88,89]. These enhanced nutrient levels may contribute to the superior antioxidant properties and potential health benefits of wild bilberries, making them a valuable addition to the diet. In contrast, the higher levels of cadmium and iron found in cultivated blueberries, likely influenced by soil conditions, raise concerns about the accumulation of toxic elements, which could pose health risks if consumed excessively over time. Additionally, the variability in extraction efficiency of beneficial minerals between fresh and dried forms highlights the need for careful selection and preparation of these fruits to maximize their nutritional value [89].

Additionally, another group of researchers investigated the mineral content of European cranberry (*Vaccinium oxycoccos*) and European bilberry (*Vaccinium myrtillus*), both popular wild fruits in Latvia, alongside commercially cultivated American cranberry (*Vaccinium macrocarpon*) and highbush blueberry (*Vaccinium corymbosum*). The study focused on twelve essential elements (N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Mo, B) across 136 berry samples. Results indicated that while macroelements such as K, Ca, and S were comparable in both wild and cultivated cranberries, significant differences were observed in N, P, and Mg levels in cranberries, and in Ca, K, Mg, and S levels in blueberries. Wild bilberries exhibited significantly higher manganese (Mn) concentrations than cultivated blueberries, attributed to variations in soil pH. In contrast, cultivated varieties showed elevated iron (Fe) and molybdenum (Mo) levels due to fertilization practices. Overall, wild *Vaccinium* species offer superior mineral profiles, contributing more significantly to human nutrition than cultivated varieties [90]. This difference in results underlines the importance of the need to source berries from wild habitats for superior health benefits with lower levels of contaminants. Besides, dietary choices should include a greater focus on wild bilberries for nutritional advantages in their health by having lower levels of toxic elements, and the overall benefits to human health.

7. Pest and Disease Management

Integrated Pest Management (IPM) is a sustainable and holistic approach to pest control that integrates various chemical and non-chemical methods. This ecological strategy aims to minimize risks to human health and the environment while effectively managing pest populations. By considering factors such as pest biology, environmental conditions, and sustainable practices, IPM employs a range of tactics to prevent pest prevalence, monitor infestations, and implement appropriate control measures [7,91].

Interest in beneficial microorganisms as biological control agents has grown due to their vital role in Integrated Pest Management [92]. These microorganisms—bacteria, fungi, and viruses—are available for managing plant diseases and pests [93]. However, their effectiveness can vary in field conditions due to biotic and abiotic factors [94]. Biological control targets the suppression of plant pathogens through natural organisms [95]

While synthetic pesticides provide quick disease management, they pose risks to human health and disrupt beneficial microorganisms that aid plant growth. Therefore, exploring biological control as an eco-friendly alternative is crucial for sustainable disease management. This approach not only controls plant diseases but also enhances soil fertility. This paper reviews the mechanisms by which microorganisms combat plant diseases, emphasizing their potential as effective alternatives to chemical pesticides [96].

However, blueberry is vulnerable to various postharvest diseases, including fungal infections such as gray mold. These pathogens, primarily caused by fungi and bacteria, can significantly impact fruit quality and yield [97]. Gray mold is caused by *Botrytis cinerea*, a necrotrophic fungal pathogen that significantly impacts blueberries. This opportunistic pathogen primarily infects compromised tissues, leading to blossom blight and fruit rot, which can result in substantial economic losses [98]. *B. cinerea* survives overwinter as dormant mycelia or sclerotia, with initial symptoms typically observed during the bloom phase, potentially culminating in the abortion of fruit clusters. As a polycyclic pathogen, *B. cinerea* can infect blueberries both preharvest and postharvest, with symptoms frequently manifesting during storage under humid conditions [99].

Integrating environmentally friendly methods into blueberry production enhances fruit rot management through several logical approaches. First, transitioning to closer in-row plant spacing (1 m or less) improves canopy light interception, which reduces the incidence and severity of fruit rots. This increase in light exposure stimulates flavanol biosynthesis in the fruit exocarp, enhancing resistance to pathogens such as *Botrytis cinerea* [100,101]. Additionally, utilizing biopesticides like *Bacillus subtilis* offers an alternative to chemical fungicides, as these naturally occurring microorganisms inhibit pathogen growth through competitive exclusion and activate plant defense mechanisms [102,103].

A group of researchers focused on habitat management strategies highlighting the role of conserving natural enemies in enhancing biological control within Integrated Pest Management (IPM) for highbush blueberry. The research investigated how manipulating edaphic arthropod communities and managing ground cover between blueberry rows influence insect predation. The findings revealed that different boundary types significantly affected arthropod abundance, with ingress plots exhibiting the highest levels of predatory arthropods [104]. This suggests that allowing selective movement into plots fosters a more robust natural enemy community, ultimately enhancing pest control. Moreover, implementing diverse ground covers, such as clover, ryegrass, and buckwheat, increased populations of beneficial ground beetles which are vital for pest suppression [104,105]. These habitat management practices not only help conserve beneficial insects but also reduce the dependence on broad-spectrum insecticides necessary for meeting quality standards in blueberry production. By integrating these strategies into existing IPM programs, growers can promote sustainable pest management that leverages natural enemies, contributing to ecosystem health and agricultural productivity [106].

Ground manipulation and mulching are effective cultural control methods that can enhance Integrated Pest Management (IPM) specifically for blueberries (*Vaccinium corymbosum*. Study of Rendon et al., 2019 explored how different mulches—black polypropylene weed mats, sawdust, and wood chips—impact temperature, relative humidity, and the emergence of *Drosophila suzukii* from larvae and pupae in blueberry crops. The results showed that larvae experienced lower survival rates and longer exposure to high suboptimal temperatures above ground compared to those buried below. While there was some evidence that weed mats reduced adult emergence at one site, the mulch type generally had minimal impact on temperature and relative humidity across most locations. Although weed mats may not significantly modify environmental conditions, they effectively serve as a barrier, preventing *D. suzukii* larvae from reaching favorable pupation sites in the soil. This highlights the potential of mulching as an IPM strategy to manage this invasive pest in blueberry production [107].

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Another pest affecting the genus *Vaccinium* is the Japanese beetle (*Popillia japonica*), which poses a serious threat to blueberries (*Vaccinium corymbosum*). Adult beetles feed on foliage, while their grubs damage roots, leading to wilting and reduced plant growth. Farmers often rely on insecticides for control, but entomopathogenic nematodes present a promising alternative [108]. Therefore, study of Renkema & Parent, 2021 evaluated the effectiveness of two entomopathogenic nematodes species, *Heterorhabditis bacteriophora* and *Steinernema scarabaei*, on grubs beneath various mulches, including compost, woodchips, and sawdust. Laboratory results showed that *H. bacteriophora* achieved nearly 100% grub mortality across all mulch types, while *S. scarabaei* was less effective and variable. Notably, a combination of compost and woodchips/sawdust alone caused 60% grub mortality without nematodes. However, in a field experiment conducted in October, grub mortality reached only 50%, likely due to low soil temperatures. These findings suggest that *H. bacteriophora* can effectively manage Japanese beetle grubs in blueberries, and using compost and woodchip/sawdust mulches may further suppress grub populations when applied under optimal temperature conditions [108].

Integrated Pest Management is a sustainable approach that combines various strategies—cultural, biological, physical, and chemical—to effectively manage pests while minimizing environmental impact [109]. By reducing reliance on chemical pesticides, IPM enhances crop productivity, supports biodiversity, and promotes soil health [106]. As agriculture evolves, adopting and innovating IPM principles will be essential for sustainable food production and environmental protection.

8. Chemical Composition and Nutritional Value

Berries are rich in antioxidant phytochemicals and valued for their health benefits, primarily due to complex anthocyanin profiles, flavonols, phenolic acids, and flavanols. Bilberries (*Vaccinium myrtillus L.*) and blueberries (*Vaccinium spp.*) contain over 650 anthocyanins, with cyanidin-3-O-glucoside being the most prevalent [110]. Key anthocyanidins include cyanidin, delphinidin, and malvidin, differentiated by hydroxyl and methoxy groups [111]. Flavonols like quercetin and myricetin offer antioxidant and anti-inflammatory effects [112], while proanthocyanidins enhance antioxidant activity [113]. Common phenolic acids include chlorogenic and neochlorogenic acids, linked to therapeutic effects against diseases such as Parkinson's and gastric cancer [114]. Ellagic acid is noted for its ability to lower cholesterol and blood pressure, emphasizing the nutritional importance of berries [115].

The study by Burdulis et al., 2009 examined the differences between bilberries (*Vaccinium myrtillus*) and blueberries (*Vaccinium corymbosum*) in terms of anthocyanin composition, antimicrobial properties, and antioxidant activities. Bilberries were found to have cyanidin as the dominant anthocyanidin, while malvidin was predominant in blueberries, with the highest total anthocyanin content observed in blueberry skins. Both fruit extracts exhibited antimicrobial activity, particularly against *Citrobacter freundii* and *Enterococcus faecalis*. In terms of antioxidant activity, the blueberry cultivar "Berkeley" had the highest at 82.13%, compared to bilberries at 63.72%. Notably, the cultivar "Coville" showed the lowest antioxidant activity among blueberries. Overall, bilberries are distinguished by higher levels of cyanidin and significant antioxidant properties, whereas blueberries offer greater diversity in anthocyanins and stronger antioxidant effects [116].

A recent study by Hellström et al., 2024 analyzed the chemical composition of wild bilberries and cultivated blueberries to differentiate between the two based on their phenolic profiles. A variety of samples from different geographical origins were examined using liquid chromatography, revealing significant differences in major phenolics like anthocyanins, chlorogenic acid, and condensed tannins. Wild bilberries displayed a more uniform genetic makeup and less variation in chemical composition compared to the diverse backgrounds of cultivated blueberries, which allowed for successful differentiation based on anthocyanin and tannin profiles. While both fruit types shared common anthocyanins, bilberries had higher proportions of anthocyanidin-glucosides. Principal component analysis confirmed these distinctions, although it could not determine geographical origins. The findings underscore the potential of phytochemical profiling to detect bilberry

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adulteration in processed products, highlighting its usefulness for ensuring authenticity in berry-based foods and broader applications in food safety and quality control [68].

Bilberry is gaining attention for its health benefits similar to other blueberry varieties. Rich in anthocyanins, bilberries may help with conditions like dysentery, diarrhea, menstrual irregularities, and cataracts. It is suggested that bilberries could also benefit type I and II diabetes and cardiovascular health, although further research is needed. Anthocyanosides in bilberries may enhance rhodopsin production, aiding night vision, while their tannins offer anti-inflammatory properties, underscoring their therapeutic potential [117].

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Overall, blueberries, including bilberries, are known for their potent antioxidant properties and serve as natural antidiabetic, anti-aging, and cardio-protective agents. They support eye health, bone strength, and cartilage integrity, while also assisting in weight management, blood pressure control, and cholesterol regulation. Key phytochemicals, such as anthocyanins, chlorogenic acid, procyanidins, and flavonoids, play significant roles in these health benefits, with anthocyanins comprising 84% of the phenolic compounds responsible for antioxidant activity (Table 2) [117].

Table 2. The carbohydrate, amino acid, vitamin, and mineral composition of bilberries and blueberries per 100 grams (Adapted from [117].)

Nutrients	Bilberries	Blueberries
Carbohydrate		
Sugar	14.7 g	9.96 g
Dietary Fiber	3.6 g	2.4 g
Starch	0	0.03 g
Sucrose	163 mg	0.11 g
Glucose	7222 mg	5 g
Fructose	7355 g	5 g
Galactose	0	0
Maltose	0	0
Amino Acids		
Tryptophan	3 mg	3 mg
Isoleucine	23 mg	23 mg
Threonine	20 mg	20 mg
Lysine	13 mg	13 mg
Leucine	44 mg	44 mg
Cysteine	8 mg	8.8 mg
Tyrosine	9 mg	9 mg
Valine	31 mg	31m g
Glutamic acid	91 mg	91 mg
Aspartic acid	57 mg	58 mg
Glycine	31 mg	31 mg
Alanine	31 mg	31 mg
Phenylalanine	26 mg	25 mg
Histidine	11 mg	11 mg
Vitamins		
B1	0	0.037 mg
B2	0	0.041 mg

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B3	0.4 mg	0.418 mg
B5	0.1 mg	0.124 mg
B6	-	0.052 mg
B9	6 mg	0.005 mg
A	54 I.U.	54 I.U.
Acorbic acid	9.7 mg	9.7 mg
Choline	6 mg	6 mg
Betaine	0.2 mg	0.2 mg
Minerals		
Fe	0.3 mg	0.28 mg
Ca	6 mg	6 mg
P	12 mg	12 mg
Mg	6 mg	6 mg
Na	1 mg	1 mg
K	77 mg	77 mg
Zn	0.2 mg	0.16 mg
Mn	0.3 mg	0.34 mg
Se	0.1 mg	0.1 mg
Cu	0.1 mg	0.06 mg

*I.U.= International Unit.

Based on the nutritional comparison in the **Table 2**, bilberries exhibit several notable differences from blueberries. Bilberries have a higher carbohydrate content, particularly sugars (14.7 g compared to 9.96 g in blueberries), contributing to their sweeter taste. They also provide more dietary fiber (3.6 g vs. 2.4 g), which can enhance digestive health. When it comes to amino acids, both bilberries and blueberries show similar profiles, with only slight variations in specific amino acid content. In terms of vitamins, bilberries offer higher levels of certain B vitamins, particularly B9 (6 mg compared to 0.005 mg in blueberries), while both berries provide equal amounts of vitamins A and C. Mineral content in bilberries is generally comparable to blueberries, though bilberries contain slightly more iron (0.3 mg vs. 0.28 mg) and a similar concentration of other essential minerals.

Overall, bilberries and blueberries are both nutritious choices that provide comparable health benefits, making them valuable additions to a balanced diet. Their similar nutrient profiles, including essential vitamins, minerals, and antioxidants, contribute to their roles in promoting overall health and well-being.

9. Yield and Production Analysis

Climate change is significantly influencing global food production, necessitating a deeper understanding of its impact on agri-food systems to ensure future food security. With the global population projected to exceed 9.7 billion by 2050, the challenge of increasing food supply is exacerbated by shrinking agricultural land due to urbanization. Furthermore, rising demand for high-quality foods from an expanding middle class adds additional strain [118]. Climate-related factors, including rising temperatures, droughts, extreme weather events, and increased atmospheric CO_2 levels, are already contributing to decreased yields and lower quality in staple crops across the globe [119,120].

Yield refers to the amount of agricultural product, such as fruits, vegetables, or grains, harvested from a specific area of land over a certain period [121]. In the context of crops like bilberries, yield is typically measured in terms of the weight or volume of berries produced per hectare or acre. Yield is influenced by various factors, including soil quality, climate conditions, farming practices, pest management, and plant health [121,122]. Higher yield indicates more efficient or productive cultivation, while lower yield may point to challenges such as poor soil conditions, disease, or inadequate growing practices [121].

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The study by Elisabetta et al. (2013) focused on the analysis of bilberry (*Vaccinium myrtillus*) productivity and its nutritional qualities in different environmental conditions. It compared bilberry plants growing in open habitats with those in forested areas in the Italian Alps. The researchers found that plants in open habitats produced more fruits due to greater light availability, while those in shaded forests had lower yields. The study also highlighted that the bilberries from both environments exhibited similar nutritional profiles, with high levels of macro- and microelements and bioactive compounds like anthocyanins, which are known for their antioxidant properties. This research suggests that semiwild cultivation in open habitats could enhance bilberry production while maintaining its valuable nutritional qualities [123].

In the study conducted by Nestby et al. (2013), the yield of bilberries was found to be significantly influenced by various factors, including soil fertility, climatic conditions, and pest pressures. The researchers observed that older pine forests, particularly those aged between 40 and 80 years, produced notably higher fruit yields compared to younger stands. They highlighted the importance of proper fertilization practices, particularly the application of nitrogen and phosphorus, which can enhance growth and productivity. However, they also cautioned that excessive nitrogen could lead to nutrient leaching, negatively affecting overall yields. The study pointed out that environmental stresses, such as late frost events during the flowering stage and drought conditions, can severely impact fruit set and development, resulting in reduced production. Furthermore, management practices, like cutting tillers, may cause a temporary decline in yields, sometimes persisting for up to two years. Thus, the findings emphasize the need for a comprehensive approach that integrates effective soil management, pest control, and strategies to mitigate adverse environmental conditions to optimize bilberry yields in Norwegian forests [46].

Moreover, another study by Nestby et al., 2014 examined the potential for cultivating bilberry on agricultural land. The researchers investigated the effects of nitrogen (N) and phosphorus (P) fertilization, as well as the addition of natural peat mulch, on plant growth and fruit yield. Their findings indicated that N fertilization was particularly effective, significantly boosting both spatial growth and fruit production. When combined with P, the growth and yield further improved. Peat top-dressing enhanced plant growth but did not have a noticeable effect on fruit numbers. The study concluded that bilberry can be successfully cultivated on agricultural land, provided that pH levels are optimized using acid-forming fertilizers and other soil amendments [43]. In contrast, study of Zhang et al., 2023 examined the effects of nitrogen (N), phosphorus (P), and potassium (K) ratios on blueberry yield and quality using an L9 (33) orthogonal experimental design. It revealed that potassium (K) was the most critical factor, with fertilization treatments yielding an average 37.78% higher than the control. Even the least effective treatment showed improvements in single fruit weight and phenolic content. The optimal fertilization combination was N1P2K2 (F2), comprising 100 g of nitrogen (N), 25 g of phosphorus pentoxide (P_2O_5), and 25 g of potassium oxide (K_2O) per plant, applied as ammonium sulfate, superphosphate, and potassium sulfate [124]. Both studies highlight the importance of nutrient optimization in berry cultivation, emphasizing that specific nutrient requirements can vary significantly between species.

As bilberry is native to northern Europe, a study conducted in Finland investigated the impact of temperature and clone origin on berry yield. Researchers compared northern and southern bilberry clones grown at two different temperatures, 12 °C and 18 °C, over two growing seasons. In the first year, 2008, no significant differences in berry yield were observed between the temperature treatments. However, in 2009, northern clones cultivated at 18 °C demonstrated significantly higher yields, which researchers attributed to improved flower bud formation from the previous season. Interestingly, northern clones also ripened more quickly at the cooler temperature of 12 °C, underscoring their adaptation to the cooler climate of their native habitat. While lower temperatures promoted earlier ripening, the warmer temperature resulted in greater overall yields, emphasizing the complex interplay between climate adaptation and optimal growth conditions for bilberries. This research provides valuable insights into how environmental factors influence bilberry cultivation and suggests that selecting the appropriate clone and temperature can enhance berry production [125].

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The physiological performance and fruit quality responses of the highbush blueberry cultivar Legacy (*Vaccinium corymbosum*) to high temperatures (HTs) were studied through a field experiment. During the 2022/2023 season, three-year-old plants were subjected to two treatments: ambient temperature (AT) and HT (5 °C ± 1 °C above ambient). A maintained diurnal temperature difference of about 5.03 °C between AT and HT showed that HT significantly decreased CO_2 assimilation (Pn) by 45% and stomatal conductance (gs) by 35.2% compared to AT, with intercellular CO_2 concentration (Ci) approximately 6% higher in HT plants. Fruit weight and equatorial diameter were reduced by 39% and 13% under HT, while firmness and total soluble solids (TSS) increased; titratable acidity showed no change. The Pn reduction under HT was associated with both stomatal and non-stomatal limitations, providing insights into HT effects on fruit growth and quality in *V. corymbosum* [126].

With increasing water limitations due to frequent droughts and competition for resources, blueberry growers are increasingly pressed to limit irrigation in drier years. To identify critical irrigation periods, study of Almutairi et al., 2020 evaluated the impact of soil water deficits across different fruit development stages in northern highbush blueberry cultivars (Earliblue, Duke, Bluecrop, Draper, Elliott, and Aurora) in western Oregon over two years. Results showed that soil water content and stem water potentials declined within 1–2 weeks without rain or irrigation, reaching their lowest levels in late fruit development. Water deficits reduced berry weight by 10–15% in 'Earliblue' and 'Elliott' and by 6–9% in 'Aurora' during final stages, with yield reductions primarily noted in 'Aurora'. Water deficits generally decreased fruit firmness and increased soluble solid concentrations, with mixed effects on acidity. Late fruit development, especially in midseason and late-season cultivars, proved the most vulnerable to water deficits due to high temperatures in July and August [127].

As with bilberries, where researchers investigated the effects of nitrogen and phosphorus fertilization, a group of researchers studied the effects of foliar fertilization in blueberries, focusing on calcium and micronutrient-based treatments. Foliar calcium fertilization is recommended for blueberries, which prefer low-pH soils, where calcium uptake can be limited by high Al^{3+}, Fe^{2+}, and Mn^{2+} concentrations. These foliar treatments, containing additional elements like silicon and iodine to support plant resilience, were quickly absorbed by the plants, enhancing leaf area, yield, and fruit quality traits, with berries showing increased mass, firmness, and total soluble solids, effects that also persisted post-storage. Although the treatments had limited effects on chlorophyll content, fruit color, and certain nutritional compounds, they improved fruit size and sugar content, especially with early-season harvests. Given rising global demand and production pressures, these findings suggested that foliar fertilization is a promising approach to increase yield and enhance the quality of highbush blueberries [128]. As demonstrated in both cases, fertilization strategies play a crucial role in enhancing yield and quality in berry crops, highlighting the importance of continued research into effective nutrient management practices tailored to the specific needs of different species.

Advancements in technology have enabled precision agriculture to leverage data-driven methods for improving crop yield predictions. The study by Obsie et al. (2020) utilized the Wild Blueberry Pollination Model, incorporating 30 years of field observations from Maine, USA, to assess the impact of bee species composition and weather conditions on wild blueberry yields. Using machine learning algorithms, including extreme gradient boosting (XGBoost), the researchers identified key predictor variables such as clone size, bee presence, and weather factors, with XGBoost achieving an impressive R^2 of 0.938 and minimal prediction errors. This innovative approach integrates empirical modeling with simulation to overcome traditional limitations; while empirical models offer quick predictions, their reliability can falter beyond calibration ranges. The study emphasizes the significant influence of bee diversity and weather on yields, highlighting pollination's critical role. Overall, it demonstrates the potential of advanced modeling techniques for accurate yield forecasts, especially amid climate change and limited field data availability [129].

10. Economics and Market Potential

The economic potential of bilberries (*Vaccinium myrtillus L.)* is increasingly recognized, driven by their rich anthocyanin content and health benefits, which fuel demand in sectors such as

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nutraceuticals, pharmaceuticals, and functional foods [130,131]. As consumer interest in natural, nutrient-rich products grows [132], particularly in Europe and North America, bilberries have secured a strong market position, often commanding higher prices due to their wild-harvested nature [20].

However, the economic potential of bilberries also faces certain challenges. As a wild-harvested berry, bilberry production is inherently tied to environmental factors, leading to seasonal fluctuations in supply and making it difficult to guarantee consistent year-round availability [133,134]. This seasonality introduces price volatility, where prices can increase significantly during periods of limited supply [135], but also requires producers to invest in effective preservation and processing technologies to ensure longer shelf life and market stability [136].

Incorporating circular economy principles into bilberry production presents a pathway to overcome some of these challenges while enhancing economic returns. Circular economy models emphasize reducing waste, improving resource efficiency, and creating closed-loop systems within production [137–139]. For bilberries, this can translate into sustainable harvesting practices that preserve wild populations and ensure future yields, maintaining supply chain resilience [135]. Additionally, the processing of bilberry by-products, such as skins and seeds, into secondary products like natural colorants [140], food additives [141], and cosmetic ingredients [142,143], creates new revenue streams while minimizing waste.

The industry of bilberries will, therefore, have great opportunities for market expansion with the resilience of the supply chain by adopting sustainable practices and innovation that will mean long-term economic growth and competitiveness in global markets.

Blueberries have gained greater popularity than bilberries due to their versatility, widespread availability, and strong health and wellness reputation. They are suitable for various culinary uses, from fresh consumption to baking and processing into juices and jams, appealing to a broad range of consumers. Their rich nutritional profile, including high levels of antioxidants, vitamins, and dietary fiber, has led to increased demand, particularly in the U.S., the largest market for fresh blueberries [115]. Advancements in agricultural techniques, such as high-density planting and improved breeding programs, have enhanced yields and extended growing seasons, allowing producers to meet the rising global demand [144,145]. In contrast, bilberries have a more limited market presence and are primarily harvested in the wild, making blueberries a more accessible and profitable crop for growers and exporters.

When it comes to blueberries, the market potential has seen remarkable growth, with global production more than doubling in the last decade, and Mexico emerging as a key player among the top five blueberry-producing regions. This surge in production is largely driven by increasing consumer demand for fresh blueberries, known for their health benefits and versatility in various culinary applications. As the largest producer and consumer of blueberries, the U.S. market presents significant export opportunities for Mexican growers, particularly those utilizing high-tech methods such as high tunnels to enhance yield and quality. With favorable climatic conditions and advancements in agricultural practices, the potential for profitability in blueberry production is substantial, making it an attractive investment for growers looking to capitalize on this burgeoning market [146].

11. Future Prospects and Challenges

Blueberries are positioned for continued growth due to their increasing popularity in health-conscious markets. The rise in demand for fresh produce, coupled with innovations in agricultural practices, such as high tunnel farming and improved cultivars, has enhanced yield and extended growing seasons. Blueberries' versatility in culinary applications and their favorable nutritional profile contribute to a robust market potential. However, challenges include rising production costs, competition from other berry crops, and vulnerability to climate change impacts, such as extreme temperatures and water scarcity.

On the other hand, bilberries, being primarily wild-harvested, have a niche market appeal, particularly in regions where they are culturally significant. The growing interest in foraged foods

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and natural products may enhance their market potential. However, challenges abound, including limited commercial cultivation, lower yield compared to cultivated blueberries, and environmental concerns over overharvesting in the wild. Additionally, bilberries face competition from more widely cultivated berries, limiting their overall market growth.

In summary, while blueberries are poised for significant growth driven by consumer demand and agricultural advancements, bilberries will need to navigate challenges related to cultivation and market access to realize their potential.

12. Conclusion

The comparative analysis of bilberries and blueberries reveals the unique contributions each species makes to agriculture, ecology, and nutrition. Bilberries, with their rich nutrient profiles and distinct flavor, thrive in specific environmental conditions and hold cultural significance in regions where they are traditionally harvested. Their wild-harvested nature offers sustainability advantages, though challenges such as climate variability and limited commercial cultivation affect their market potential. Conversely, blueberries benefit from broader cultivation practices and increased global demand, largely due to their adaptability and higher yields. While mechanization in blueberry harvesting improves efficiency, it raises ecological concerns that must be addressed to maintain sustainable practices. Both berries are rich in antioxidants and offer diverse health benefits, highlighting the value of integrating them into a balanced diet. As consumer interest in natural products grows, the future success of both bilberries and blueberries will depend on sustainable practices, innovative production methods, and the ability to navigate the challenges posed by climate change. Ultimately, both species enrich the *Vaccinium* genus and contribute significantly to agricultural diversity and nutritional health.

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