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Review

Key Determinants of the Physiological and Fruit Quality Traits in Sweet Cherries and Their Importance in a Breeding Programme

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Abstract: Australia produces high-quality sweet cherries and generates revenue from local and export markets. Due to increased demand in the markets, the area of sweet cherry production has increased in Australia. Sweet cherry breeding and production have challenges such as self-incompatibility genotypes and phenotyping of agronomic, physiological, and quality traits. Understanding these traits and their interaction with environmental factors would increase production and provide better economic returns for the industry. This review paper covered the challenges of current sweet cherry production, breeding efforts, the basis for understanding of plant traits, the influence of environmental factors on the traits, and opportunities for new sweet cherry breeding in the future. The period of flowering and maturity along with firmness of the fruit are key traits in cherry production. Breeding techniques such as haplotype breeding will contribute to improving breeding efficiency and deliver better cultivars of sweet cherry.

Keywords: environmental factors; fruiting spur; fruit development; genetic resources; pollination

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Citation: Devasirvatham, V.; Tan, D.K.Y. Key Determinants of the Physiological and Fruit Quality Traits in Sweet Cherries and Their Importance in a Breeding Programme. *Horticulturae* **2022**, *8*, 694. https://doi.org/10.3390/horticulturae8080694

Received: 29 June 2022
Accepted: 27 July 2022
Published: 1 August 2022

1. Introduction

Sweet cherries (*Prunus avium* L.) are usually grown in the climatic zones and belong to the Rosaceae family. It is an outcrossing and self-incompatible species, which means self-incompatible cherry plants reject their own pollen germination and pollen tube growth on the stigma and accept outcrossed pollen usually from a different cultivar. Therefore, open and self-pollinated cherry cultivars are commonly used around the world in sweet cherry breeding programs. Many sweet cherry cultivars were developed with various traits (agronomy, physiology, and fruit quality) in many countries [1]. Normal bud breaking and flower blooming requires chilling hours (temperature ranges between 2 °C and 9 °C for ≥800 h) followed by warm temperature for fruit development (18 °C). The temperature and chilling units are usually calculated based on the Richardsen model in Australia, Europe, and part of the USA. Alternatively, the Eriz chill model can also be used for chilling calculations in areas having inadequate chilling hours (e.g., California, USA) [2]. Therefore, bud initiation and flowering depend on the cultivar, physiological condition of the tree, and weather.

Turkey ranks first in the world in sweet cherry production [3]. Australian cherries are grown in six states. New South Wales, Victoria, Tasmania, and South Australia rank in the top four states in Australian cherry production. These states meet the demand of local markets and export part of their production. Australian cherries are available from mid-October to late February depending on the variety (early, mid, and late), climatic variation, and growing seasons [4]. Australia produces 20,000 tonnes of sweet cherries per year, which costs A$189 million, and exports 5000 tonnes, which is worth A$80 million [5]. Early season fruits (mid-October) are available on the market, which are produced from the Hillston and

Narromine areas of New South Wales. The late season fruits are available until late February, mainly from Tasmania. Early maturing cherries may have varying yields due to seasonal changes and receive a premium price on the market. Commercially, fruit size will also determine the market price. Early maturing cultivars are Merchant, Chelan, Glen Red, Glen Rock, and Royal Dawn. Mid-to-late maturing cultivars are Bing, Van, Stella, Sylvia, Simone, Lapins, Kordia, Sweet Georgia, Regina, and Sweet heart [2]. Due to outcrossing and self incompatibility, growers expect synchronised flowering among the cultivars (early, mid-, and late-maturity groups) to achieve successful pollination. If unsynchronised pollination occurs, pollinators are essential in the orchard. The role of pollinators has to be studied along with the genetic diversity of sweet cherry germplasm and the period of pollination in Australian cherry production. Several agrotechnical practices have been adapted worldwide, including Australia, to achieve good fruit quality, particularly fruit firmness, larger fruit size, colour, and sugar content. A common technique to achieve high quality fruits in heavy bearing sweet cherry cultivars is thinning of flowers and fruits [6]. Other techniques such as using plant growth regulators, girdling, and fertigation can improve fruit set and quality in low-fruit-bearing sweet cherry cultivars [7].

In Australia, most cherry trees are grown in the bush system due to extreme summer temperatures. Almost all the growing areas have early, mid, and late cultivars to meet the impact of environmental factors such as variable temperatures and rain. Some orchards have rain covers to protect from rain, hail, and wind damage which can cause cracks in the skin during fruit maturity. Sweet cherry production has challenges from drought and pests such as the Queensland fruit fly and European earwig. The damage from European earwigs has been increasing in grain crops such as canola, lucerne, lupins, and lentils [6] and horticultural crops such as apples and sweet cherry [7].

In recent years, sweet cherry production has been increasing in Australia. Therefore, the sweet cherry breeding program needs to identify crop physiological traits, fruit quality, yield, and maturity period and correlation among traits. Marker-assisted selection including Quantitative Trait Loci (QTL) associated with targeted traits will add value to the sweet cherry breeding program in the future. This review paper explains phenotyping of physiological traits, quality traits, the impact of environmental stress and the breeding program of the sweet cherry.

2. Phenotyping Based on Agronomic and Physiological Traits in Sweet Cherries

Phenotyping is identified as an interaction between cultivars and plant responses to different environmental conditions which determine the plant yield and fruit quality. Efficient phenotyping techniques are important to develop new sweet cherry cultivars in Australia with high yield potential, high fruit quality, temperature tolerance (cold and heat), and drought tolerance.

2.1. Agronomic Traits

The important agronomic traits of sweet cherry are blooming and fruit development and have a direct influence on maturity [8]. Fruits from early and late-maturity cultivars attract a higher price on the market [9]. For both maturity groups, the periods of bud breaking, blooming, and maturity are important traits in sweet cherry production [10]. The positive correlation between blooming and maturity period has been observed in peaches and apricots [11,12]. Breeders need knowledge of the blooming and fruit development for various sweet cherry germplasm and the impact of cold and high temperatures during that period.

Sweet cherry has three stages of fruit development (double sigmoid growth pattern). In Stage 1, cell division and enlargement of the pericarp occurs. In Stage 2, embryo development occurs, which causes pit hardening. Usually, Stage 2 is shorter in early cultivars than late cultivars and has a high chance for abortion [13]. Cold temperature during Stage 2 in early cultivars was the main reason for embryo abortion [14]. Day temperature ≤ 16 °C had an adverse effect on embryo development in sweet cherry [15]. The pit hardening stage was also susceptible to low temperatures in stone fruits [16]. Particularly, sensitivity of temperature in sweet cherry endures the transition period from Stage 1 to Stage 2 and temperature also had an impact on fruit quality [15]. Fruit development was studied from peak blooming to fruit maturity using cumulative growing degree days (CGDD) [17]. The base temperature for the peak blooming period was 4 °C. For example, the most popular mid-season cultivar, Bing, needs ≥ 800 chilling hours and 683 positive chilling units during 30% bud breaking period in Orange (NSW), Australia. This indicates that the Bing cultivar has a high chilling requirement in Stage 1 [18]. Optimum (24 °C) and critical temperatures (>35 °C) for cherry fruit development were also identified [17]. Duration of Stage 2 was increased due to cold temperatures (4 °C to 15 °C) for late-maturing cultivars [17]. The critical temperature of >35 °C during fruit development for sweet cherry is similar to seed development in grain crops such as wheat [19], chickpea [20], and peanuts [21]. Stage 3 of cherry fruit development consists of continuation of fruit growth and ripening of the exocarp (fruit flesh). It is a critical period to achieve high yield and fruit quality. The optimum temperature during Stage 1 and Stage 2 fruit development has a major influence on Stage 3 fruit development [15]. Hence, temperature is a key factor influencing flowering and fruit development.

Rootstocks regulate the subsequent tree growth, management of the orchard, and crop yield. It is also important that the selection of rootstock has to match the environmental condition of the orchard [2]. In Australia, Mazzard rootstocks are compatible with most sweet cherry cultivars and the Mahaleb rootstock is incompatible with Australian sweet cherry cultivars [2]. The influence of rootstock on the sweet cherry cultivar affects the timing of flowering, the intensity of flowering, fruit quality, and yield [22]. The influence of rootstock on the flower bud sensitivity to frost (−5 °C to −7 °C) was studied in Belgrade. Rootstock affected the flower bud blooming time, flowers per bud, timing of harvest, fruit weight, and yield [22]. Rootstocks also influence the number of flowers and percentage of fruit set. However, certain cultivars had impaired pollen viability and pollen germination under frost [23]. For example, the 'Kordia' cultivar had small pollen grains and poor viability. The cultivar 'Regina' had more frost resistance than 'Kordia' [22]. These cultivars have a great impact on the selection of rootstock in the breeding programme. Therefore, the rootstocks influence the performance of the sweet cherry cultivars and have an effect on tree growth, crop yield, flowering, and pollination. Though the influence of rootstocks on the cultivar is mentioned in this section, the importance of rootstocks in sweet cherry breeding is discussed in greater detail in Section 5.

2.2. Physiological Traits

Australian sweet cherry tree growth stages and physiological process are outlined in Figure 1. Each stage is influenced by tree density, genetic material, temperature, and water availability. The key physiological drivers for fruit growth in sweet cherry are photosynthesis and carbon–nitrogen mobilisation of tissues. Different tree planting systems are being used commercially in Australia. Simplified tree structures encourage light penetration and photosynthesis. Therefore, leaf traits are important physiological traits in sweet cherry breeding. The leaf length and width had a positive correlation with fruit weight in sweet cherry [24]. Consequently, the role of photosynthesis and leaf size (length and width) are important in determining fruit size [25,26]. Higher photosynthetic productivity and leaf size could be achieved with higher light interception in the sweet cherry tree [27].

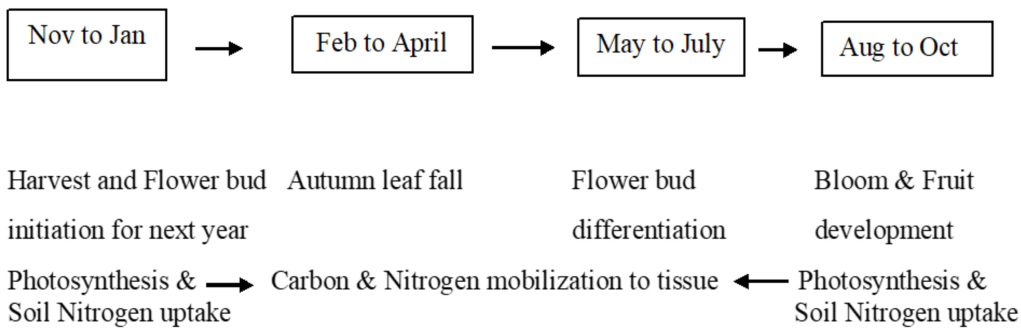

Figure 1. Australian cherry stage of development and physiological process.

On the other hand, sweet cherry trees are deciduous and leaves develop after blooming and this happens throughout fruit development. Net photosynthesis productivity was maintained from fruit development (Stage 2) to fruit maturity (Stage 3) [28]. Thus, maintaining a good tree canopy, including the leaf population, is important to achieve maximum photosynthesis. Different training systems using trellis have been adapted in the sweet cherry orchard to maintain the tree canopy and fruiting units. The knowledge of leaf population including size and fruiting units is vital to all training systems. Generally, leaves supply sugars to the fruits, which encourages them to produce fruiting units and influence fruit quality [29]. The fruiting units of a 4-year-old tree are enhanced by pruning. The pruning encourages the leaf to fruit ratio (crop load) that increases fruit size and quality [30,31]. Strategic pruning increases the source of photo-assimilates (carbohydrates from leaves of spurs from 2nd- and 3rd-year branch and current-year leaves) and nitrogen demand by sink (buds, flowers, fruits) [32,33]. In addition to annual pruning, hand thinning of buds, flowers, and young fruits improves crop load and progresses the photo-assimilate supply among developing fruits [34]. Pruning along with foliar N application on the mature leaves in Stage 3 of fruit development increased the fruit quality [33].

Photosynthesis and its impact on yield and quality indices such as fruit weight (g), fruit sugar content (sweetness), and fruit firmness (firm to very hard) are directly influenced by the rootstock and scion cultivars. Hence, the rootstocks (dwarf and semi-dwarf) influence tree density in the orchard. The sweet cherry cultivars from different maturity groups such as Burlet (early), Summit (mid), and Van (late) growing on five rootstocks (*Prunus avium* L.—vigorous; CAB11E—semi-vigorous; Maxma14—semi-dwarfing; Gisela5—dwarfing; Edabriz—very dwarfing) determined the physiological traits of stem water potential, stomatal conductance and photosynthesis, which directly influenced the fruit weight, firmness and sweetness [35]. Furthermore, the use of inter-stem (grafting a third genetic material) between rootstock and cultivar (scion) with planting system to understand photosynthesis and crop yield was attempted. Trees on inter-stem had higher yields due to the periphery leaves of the tree canopy, which produced higher dry-matter content per unit of leaf surface area and net photosynthetic productivity, which led to bigger fruits and better yield [27]. Therefore, physiological traits of photosynthesis, stem water potential, and stomatal conductance are controlled by rootstock, scion cultivar, and rootstock x scion cultivar interaction, which directly affect fruit quality.

2.3. Impact of Environmental Factors in Agronomic, Physiological and Reproductive Traits

Generally, each stage in fruit development is affected by temperature. Flower bud differentiation was slow when average temperatures reached above 18 °C, which indirectly caused shorter fruit development periods [36]. Temperature has a direct influence on the period of fruit development on Stage 1. Low temperature (<12 °C) combined with rain negatively influenced the pollination and activity of bees and fruit set [37,38]. Generally, honey bees are active pollinators at or above 19 °C and completely cease their activity at <13 °C. Wind speeds at >8 km/h and rain also stop honey bee activity. In Tasmania, cherry growers use bumblebees as a pollinator to achieve effective pollination because bumblebees are active under cold and wet conditions [2]. Five bee species that are active at low temperatures (≤12 °C) combined with rainy days were identified in Turkey [37]. Hence, there are potential alternative pollinators which can be active in adverse climatic conditions to achieve economic returns from the cherry orchard. Simultaneously, high temperatures (>30 °C) during flowering time, particularly the differentiation of pistil primordia (stigma, style, and ovary) created double fruits [38,39]. High temperatures (29 to 35 °C) during the harvest period caused an increase in the number of double fruits [40]. Furthermore, high temperatures accelerate pollen hydration and ovule senescence in sweet cherry [41]. Therefore, extreme temperatures (too cold—>0 °C and too hot—≥35 °C) have a negative impact on reproductive organs in sweet cherry and reduce crop yield by shortening the period of fruit development.

Another factor which influences agronomic and physiological traits in sweet cherry production is water supply. Most Australian cherry production areas have limited water supply and need careful water management in the cherry orchards [2]. Generally, the harvest period for sweet cherries in Australia relies on a warm summer with less rain. In the fruiting period, the tree continually develops leaves and flower buds for the following season (Figure 1). It is common for fruit growers to apply water during the harvest period to match summer temperatures. The amount of water supply at this stage depends on crop age, planting density, and climatic conditions of the orchard. For example, the average daily water uptake of the 4 years old trees (early cultivar 'Rita') in a high-density orchard (spacing 4 m × 2 m) during summer (May to July) in Hungary was 23–24 L per tree [42]. Water stress (where tree demand exceeds the supply) at harvest can cause interruption in photosynthesis, leading to changes in biochemical processes in leaves such as leaf sugar content [43]. Regulated deficit irrigation (RDI) 65% of crop evapotranspiration during harvest was monitored by stem water potential rather than fruit water potential. RDI (65% of crop evapotranspiration) during harvest did not affect the current year's fruit yield and quality [44]. Irrigation with 85% of crop evapotranspiration during preharvest and 55% of crop evapotranspiration at postharvest did not affect flowering, fruit set, and fruit growth [40]. However, irrigation during preharvest and postharvest periods which did not meet plant water requirements decreased vegetative growth and leaf area: fruit ratio, which subsequently affects fruit size. Consequently, regulated deficit irrigation which meets plant water requirements in critical periods of flowering and fruit development saved up to 40% irrigation water without decreasing fruit yield [45]. Sweet cherry phytochemicals (total sugars, total organic acids, and anthocyanins) in fruits were higher in irrigated trees (rain water plus 100% evapotranspiration) than in non-irrigated trees (only rain water) [46]. Therefore, adequate chilling hours during blooming, optimum temperatures during fruit development, water supply based on tree demand during flowering, and fruit development encourage good sweet cherry fruit quality and crop yield.

3. Phenotyping Based on Fruit Quality Traits in Sweet Cherries

From the commercial point of view, the key sweet cherry fruit quality traits are fruit size, fruit colour, firmness, and sweetness [30,47,48]. The Australian cherry production guide explains the quality descriptions for fruit size, fruit colour, sweetness, and firmness tester. The fruit size varies from 22 mm to 32 mm (in diameter) (Figure 2). The price of cherries varies with size, along with its firmness, fruit colour, and sweetness. Fruit firmness is an important trait in cherry quality, which is usually tested by fruit firmness tester (or) penetrometer and expressed as g/m^2. Fruit sweetness is determined by soluble solid concentration using a digital refractometer (% brix). The fruit firmness and sweetness by commercial standards from the Australian cherry production guide is explained in Table 1.

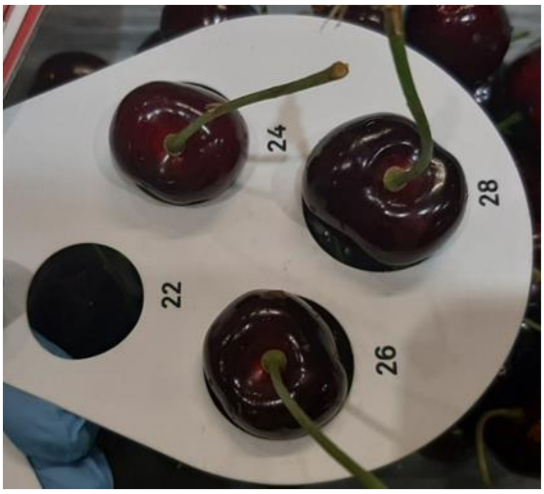

Figure 2. Australian commercial cherry size (24, 26, 28 mm in diameter).

Table 1. Sweet cherry traits of firmness and sweetness in commercial production [2,4].

Firmness	g/m^2	Sweetness	Brix %
Hard	>350	Super sweet	≥21
Very firm	300–350	Very sweet	19–20
Firm	240–300	Sweet	17–18
Less firm	<240	Moderate sweet	16

Generally, plant growth regulators have been reported to improve fruit quality traits of sweetness, firmness, and flavour in sweet cherries. Many studies showed that the growth of pericarp can be altered using plant growth regulators (e.g., gibberellic acid (GA)), consequently changing carbon partitioning into fruit and fruit quality [49,50]. The rate and time of GA application in cherry is profound. The application of GA during high rainfall produced increased fruit crack because of reduced transpiration for two days from application [51]. Commonly, the application of GA at 15–30 mg/L at the beginning of Stage 3 fruit development in early maturing sweet cherry cultivars improves fruit firmness, sweetness, and fruit colour [52,53]. For late-maturing sweet cherry cultivars, the application of GA at the end of Stage 2 at a low rate (between 10 and 25 ppm) improves fruit firmness [54] to obtain a premium price at the end of the sweet cherry season in local markets as well as for export.

Fruit cracking has been identified as a major consequence of excess amount of water (25 mL above field capacity) from rain or irrigation [51,55]. Larger-sized fruits are also susceptible to fruit cracking [51]. Reasons for sweet cherry fruit cracking include high water content within the plant and rain or precipitation on the fruit. Water content from precipitation on the fruit influences the osmotic potential in the fruit. Water moves through the xylem from the pedicel or stem. Water uptake results in three types of fruit cracking in sweet cherry [56,57]. Fruit cracking happens around the stem end, causing deep cracks inside the fruit and apical cracking at the end of the fruit.

In sweet cherry, calcium content in fruit is reported as a major reason for fruit cracking due to rain [58]. Generally, calcium in the cherry mesocarp or fruit flesh (0.41 to 0.64 mg per fruit in the 'sweetheart' cultivar) increases in the fruit development stage 2 to stage 3. However, the dry mass ratio (2.45 to 1.25 mg Ca per g of dry mass in 'sweetheart' cultivar) decreases from Stage 2 to Stage 3 [59]. This has been reported in many fruits, including apples [60] and kiwifruit [61]. The calcium dry mass ratios were two to threefold higher at the stem end than at the apical (blossom) end [59]. This indicates that the distribution of calcium is a gradient from the stem to the apical end. Furthermore, xylem fluxes from the cherry stem play a key role in importing water to the developing fruits [59]. A similar trend was observed in tomatoes [62]. Additionally, the cracking in the skin or exocarp happened due to tangential stress (stress in horizontal direction) experienced by the fruit skin in cherries [57]. Ultimately, due to stress, the weakest point of skin breaks [63]. In sweet cherry, cracking mostly happened when trees received rain, hail, and wind during the period of three weeks before commercial harvest [57]. Recently, an effort was made to avoid fruit cracking using high tunnels in sweet cherry. However, high tunnels encouraged high temperature (>27 °C) and humidity (96%) inside the tunnel and affected fruit firmness [64]. In Australia, some regions (e.g., Adelaide Hills Orchard) birds can do considerable damage to fruit. Those regions are encouraged to use net covers to protect cherries from birds [2]. In the future, more cover protection studies combined with microclimate management across different production areas and genotypes will add support to sweet cherry production. Hence, quality traits are affected by rain, hail, wind, temperature, and birds [58,64].

4. Postharvest Physiology in Sweet Cherry

Fruit quality after harvest (cold storage and export to market) plays an important role in sweet cherry economic returns. Cherries are delicate and susceptible to pitting and bruising during packing. Based on a consumer perspective, the sweet cherry quality traits are bright fruit colour, green stem, firmness, and sweetness [65,66]. Stem browning and surface pitting are two important postharvest quality attributes, which reduce the sweet cherry market price. Single application of gibberellic acid at the end of Stage 2 and beginning of Stage 3 (the end of pit hardening) improved resistance to pitting and reduced stem browning during the cold storage (0 °C) period of four weeks from harvest [54]. On the other hand, maintaining a cool chain during storage helps to maintain the quality of fruit postharvest [67]. Using a controlled atmosphere of 20% CO_2 in storage combined with 2 °C maintained fruit quality parameters such as firmness, green stem, sugar content, and low fungal diseases [67]. Most Australian cherry packing systems utilise hydrocooling to remove field heat from the fruits. The hydrocooling system is useful to maintain fruit turgor and for reducing stem browning. Tasmanian cherry packing systems mostly use forced air-cooling after harvest. Both cooling systems targets lowering the pulp temperature to between 2 and 4 °C before supplying it to consumers. Generally, fruits are packed in pre-pack punnets and bags to sell in local supermarkets. Modified Atmosphere Packaging (MAP) is also practised in Australia during storage to maintain fruit quality for domestic and export markets. The MAP contains low O_2 and high CO_2 while packing and maintains equilibrium O_2 and CO_2 concentration with the use of sealed plastic bags. Fruit respiration inside the bag will help maintain the equilibrium between the gases [68]. To attain maximum profit in Australian cherry production, it is vital to control the cold chain of the entire supply chain, including transport and at retailers, to achieve fruit quality through the consumer [67].

5. Sweet Cherry Genetic Resources for Improving Yield Genetic Gains

While the sweet cherry has been cultivated for many years, in the past 30 years, a selection of elite parents has been made in many countries including European countries, the USA, Canada, the United Kingdom, Ukraine, and Australia. Cherry genetic resources (landraces and modern cultivars) are available to utilise in the breeding programme worldwide. However, the understanding of the genetic domestication and breeding history of cherry genetic resources plays a major role in sweet cherry breeding.

Generally, commercial sweet cherry trees are developed by budding or grafting using selected scions from desired characteristics such as maturity (early or late cultivars), fruit size (≥24 mm fruit diameter), fruit colour (red to dark red), firmness (firm to very hard), and taste (sweet to super sweet) and grafted onto an appropriate rootstock [4]. Mahaleb, Mazzard, and Colt are some promising rootstocks used in cherry breeding programmes in many countries [69]. The sweet cherry varieties of Burlet, Summit and Van were influenced by selected rootstock in relationships with water uptake, photosynthesis, and fruit quality indices such as fruit size, firmness, sugar content (sweetness), and colour [35]. Hence, the growth and yield traits were greatly influenced by sweet cherry rootstock [70]. Selection of rootstock based on soil types is also important in breeding. In Australia, Mahaleb rootstock requires light textured soil (sandy), Mazzard rootstock needs loams or clay loams and Colt rootstock desires heavy soil. Dwarfing (Giessen series) and semi-dwarfing (Krymsk series) rootstock series are also popular in Australia [2]. Therefore, selection of the rootstock plays a significant role in the sweet cherry breeding programmes.

Furthermore, breeders are interested in developing self-fertile cultivars and cultivars resistant to powdery mildew. Chelan is a self-fertile early maturing variety developed by the USA and widely grown in different countries, including Australia. Sweet Early and Grace Star were developed in Italy and received interest from growers in Europe and Asia [71]. Generally, in Australia, new sweet cherry cultivars are developed by the National Cherry Breeding Program based in South Australia. A few promising cultivars were released, including self-fertile cultivars such as Sir Don, Sir Tom and Dame Roma [2].

The timing of flowering and fruit maturity are important physiological traits. Fruit firmness and fruit weight are quality traits. These traits are targeted by breeders across the globe to achieve genetic improvement. High broad-sense heritability was obtained for the timing of fruit maturity [72,73]. Fruit firmness and fruit weight are attributed to a significant role in sweet cherry breeding due to high broad-sense heritability [73].

Many studies have been conducted using different molecular markers to understand genetic diversity in sweet cherry. The sweet cherry genetic structure and changes in diversity were analysed using Simple Sequence Repeats (SSR) markers. The linkage disequilibrium of marker loci declined rapidly with physical distance, suggesting no strong structure among modern sweet cherry germplasm. These data suggest that sweet cherry has a narrow bottleneck due to repeated use of a small number of parents and crosses [74]. Further development has occurred using markers in cherry breeding. Single Nucleotide Polymorphism (SNP) markers can be useful to identify mutants among germplasm [16]. Genome-wide SNP markers were used to evaluate 597 germplasms which include parents and crosses in different locations in Europe and USA. The collective data set showed that fruit maturity timing is an important trait in sweet cherry breeding [6]. Besides, more studies are needed on cherry domestication and improvement to overcome the issue of the narrow bottleneck.

Generally, the high breeding values of unreleased offspring showed the opportunity of several individuals with commercial promise in sweet cherry breeding. This shows a broad base of genetic diversity and opportunity for sweet cherry improvement. In Australia, sweet cherry breeding is focussed mainly on wider adaptation to Australian growing conditions along with fruit size, rain cracking, and self-fertility.

There are two types of breeding programmes followed in Australia. (1) Using hybridisation, a new seedling population will develop with the targeted traits. These seedlings will be raised in the glasshouse nursery and also grown in the field nursery for one year observation. Then selected plants will grow in the field for further assessment from third year. The trees will be assessed to meet basic breeder's standards and will be subject to further fruit quality evaluation. Top ranking commercial value breeding lines will be considered for further breeding programmes. Based on hybridisation, 671 tree evaluation lines have been planted for further analysis by the South Australian Research and Development Institute (SARDI) [75].

(2) The second method of breeding is the asexual method. Rootstock selection is made based on the environmental conditions, management strategies of the orchard, and economic value. SARDI identified 131 breeding lines for further evaluation for rootstock which have a commercial interest in Australia [75]. This shows that developing populations of selected rootstock is also practised in cherry breeding. A $F_{12/1}$ rootstock population was established in Tasmania to develop a fruit cracking-resistant variety [57]. This effort was further investigated in different locations (Australia, USA, and Turkey) with a combination of $F_{12/1}$ rootstock trained on different bush systems to investigate fruit quality at harvest and post-harvest. Initial data showed that fruit cracking can be reduced with anti-transparent sprays [76]. Breeding populations of SARDI and the fruit cracking resistant

variety will be released after the National Variety Trial (NVT) in Australia in partnership with Cherry Growers Australia (CGA). World-wide collaborations in the sweet cherry breeding program will enable promising quality cherries to be produced in the future to meet the global demand.

6. QTLs Associated with Physiological and Fruit Traits in Sweet Cherries

Flowering, maturity date, and fruit firmness are important physiological and fruit quality traits in sweet cherries. These traits were studied to understand their genetic control and to identify the alleles of breeding interest. Major QTLs for flowering and maturity times were found on LG4 sweet cherry [72]. Fruit firmness QTL on LG4 was named as qP-FF4.1, which was associated with either 'soft' or 'firm' alleles [77]. These alleles are the signature of selection in the sweet cherry breeding programme. QTLs of other fruit quality traits such as fruit development time, soluble solid content, and fruit acidity were found in the same narrow region of LG4. These traits showed a positive correlation with late maturity [78]. Hence, better understanding of the genetic basis of physiological and quality traits will enable the genomic selection in sweet cherry breeding. Furthermore, a group of genes that are responsible for flowering and maturity time along with fruit quality within sweet cherry that was inherited within LG4 (haplotype) may encourage breeders to proceed with haplotype breeding. Earlier work on identification of haplotypes in the wild and in cultivars was made in cherry [79]. After identifying targeted traits in targeted environments, marker validation (genome-wide association studies/QTLs) is needed to separate traits and genes [80]. Using a small group of genotypes including wild cherry, a genome-wide association study using SNP markers was conducted to identify a wide range of phenotypic diversity in selected traits. The study identified genes responsible for flowering time, dormancy and disease resistance in sweet cherry. This study established the basis for a large-scale classification of sweet cherry germplasm. Therefore, haplotype breeding can dissect complex traits in sweet cheery. Consequently, its application for the development of improved cultivars in grain crops has already been addressed [81]. Gene editing also shows possibilities in the future for cherry breeding. Initial effort was made to understand the gene editing procedure, protocol and editing techniques in sweet cherry cultivars of Lapins and Bing. Hence, further developing the procedure of gene editing tools will progress the gene editing technique in sweet cherry [82].

7. Conclusions

Sweet cherry fruits are available from late spring and throughout summer across the globe, depending on maturity (early to late). In Australia, sweet cherry production has significant economic returns for growers and exporters but has some challenges in production and breeding perspective. Environmental factors such as extreme temperatures (low and high), water stress, and rainfall have a negative impact on cherry production. Cold temperature ($\leq$16 °C) influenced the embryo abortion in Stage 2 of flowering to fruit development. High temperature ($\geq$30 °C) during Stage 3 of fruit development affects fruit quality. Water stress during preharvest and postharvest reduced leaf area: fruit ratio and fruit weight. High preharvest rainfall increased fruit cracking. The physiological trait of photosynthesis depends on the tree canopy and leaf area which has a direct influence on crop yield and fruit quality indices of firmness, colour, and sugar content. The physiological and quality traits are generally influenced by cultivar (scion) and rootstock. Therefore, phenotyping for genetic analysis of selected traits such as flowering, fruit development, and fruit quality, including gene discovery, is important in sweet cherry production. Genetic resources of sweet cherry available worldwide are mainly derived from rootstock germplasm originating from Canada, the USA, the United Kingdom, and European countries. Hence, breeders have to develop a breeding plan including haplotype-assisted breeding to widen the genetic bottleneck to develop new cultivars with high fruit quality adapted to local environmental conditions.

Author Contributions: Conceptualisation, writing—original draft preparation, review and editing, V.D.; writing—review and editing, D.K.Y.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study did not require ethical approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We gratefully acknowledge contributions of anonymous reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

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