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Sweet cherry world research overview 2018-2020

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Abstract: This review cites 137 reports from 25 countries. The highest citation numbers originate from the USA (14), China (14), and Italy (14). In contrast, only one reference is from Hungary, Iran, Morocco, and the United Kingdom. The references are divided into 16 topics. Results or conclusions of each study are briefly described, ranging by year of publication and alphabetical order of authors. The most important topic is physiological research, which includes 31 references. Referring to the years, the most productive was 2019 with 55 references, whereas the least prolific was the previous year 2018, providing only 33 references. One report was published in cooperation with authors from two countries.

Keywords: cherries; physiological research; *Prunus avium*; review

The sweet cherry (*Prunus avium* L.) is a tree from the Rosaceae family. In agriculture, it is mostly used to produce highly demanded and delicious fruits for fresh consumption. The fruit production has an increasing tendency, as well as the number of research publications. Sweet cherry global production has an ever-increasing tendency (1.9 million t in 2000, rising to 2.77 million t in 2021) (FAO 2024). The largest growers in terms of harvest are Turkey, the USA and Chile, which account for roughly half of the global production. Research can contribute to the development of new knowledge and improve the fruit quality and safety, which supports the use of temperate fruits in the food industry. It also brings valuable answers to breeders, because a great deal of the results bring answers to the genetic background of the most important traits. The aim of this article is to bring an overview about the research conducted on sweet cherries and briefly report the main results and research trends for the near future.

TOPICS

Genetic research. High-density linkage maps of the sweet cherry were constructed in Spain (Calle et al. 2018). These maps were used for a genetic analysis of the relevant traits in sweet cherry breeding by a quantitative trait locus analysis. The self-pollination populations will be useful for investigating the inbreeding depression in a naturally outbreeding species.

Genomic heritability estimates on the sweet cherry revealed that a non-additive genetic variance was found relevant for industry-prioritised traits (Piaskowski et al. 2018). In this USA study, the genome-wide predictions were estimated using a repeated measures model for phenotypic data across three years, incorporating additive, dominance, and epistatic variance components.

Sweet cherry cultivars of Ukrainian and non-Ukrainian origin were characterised via use of microsatellite markers (Ivanovych, Volkov 2018).

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Eleven pairs of primers were applied to microsatellite loci to assess the genetic diversity and relatedness of these cultivars, resulting in the amplification of 66 SSR alleles. The application of the method allowed the elucidation of the relatedness among the varieties and confirmed that the Ukrainian cultivars combined the genetic material of local, western European, and probably Caucasian origin. However, the origin of several cultivars still remains unclear.

DNA fingerprinting of closely related cultivars was studied in Canada (Wiersma et al. 2018). The informative simple sequence repeat markers were located only in five small regions of the genome, which also contained discriminating simple sequence repeat markers and provided an explanation for the difficulty of locating simple sequence repeat markers for these cultivars.

The genetic basis of fruit firmness in sweet cherries was studied in the USA (Cai et al. 2019). Their candidate genes related to plant cell wall modification and various plant hormone signalling pathways were identified, with an expansion gene being the most promising candidate. Their results supported understanding the genetic basis of fruit firmness and enabled the use of DNA-informed breeding for this trait in breeding programmes.

In Germany, Chen et al. (2019) examined the expression of putative aquaporin genes (AQP) in sweet cherry fruits. Their results indicated that AQP are expressed in sweet cherry fruits. The expression was generally higher in the flesh than in the skin and decreased towards maturity. The AQP were also involved in water transport across plasma membranes.

Building international partnerships for the collation of historical data to study the environmental stability of genomic predictions in sweet cherry was carried out as an international research project in Australia (Hardner et al. 2019b). The larger the phenotypic dataset from environments and individuals, the greater the opportunity to identify genotype-by-environment patterns of quantitative trait loci and polygenetic effects, to generate and test hypotheses related to factors driving those patterns, and to predict the performance of individuals in multiple environments.

A DNA marker for distinguishing flesh colour was developed in Japan (Saito et al. 2019). It was possible to determine the flesh colour using one of the three DNA markers in most cultivars. However, the result suggests that the polymorphism controlling the flesh colour has yet to be defined.

The phased genome sequence of an interspecific hybrid flowering cherry was also analysed in Japan (Shirasawa et al. 2019). The genome and transcriptome data were expected to provide insights into the evolution and cultivation of the flowering cherry. The molecular mechanism underlying the flowering was proposed.

A draft of the sweet cherry genome that revealed genome-wide and local effects of domestication was published in Italy (Pinosio et al. 2020). They identified 11 domestication and 5 breeding sweeps covering 11.0 Mb and 2.4 Mb of the *Prunus avium* genome, respectively. They also detected 104 candidate genes in sweep regions involved in different processes, including the determination of the fruit texture, the regulation of the flowering and fruit ripening, and the resistance to pathogens.

A new version of a single-nucleotide polymorphism array for sweet cherries was published in the USA (Vanderzande et al. 2020). This next-generation sequencing single-nucleotide polymorphism array increased the genetic resolution and genome coverage of the original sweet cherry single-nucleotide polymorphism array. It helped increase the understanding of the genetic control of key traits and the relationships among sweet cherry individuals.

In China, Wang et al. (2020a) used long-read and Hi-C sequencing and obtained a chromosome-scale genome assembly of the sweet cherry cv. 'Tieton'. The genome annotation revealed that more than half of the genome (59.40%) was composed of repetitive sequences, and 40 338 protein-coding genes were predicted, 75.40% of which were functionally annotated. The same team used linked-read sequencing technology to achieve a high-quality reference genome assembly and annotation of the diploid sweet cherry cv. 'Tieton' (Wang et al. 2020b). The final scaffold assembly represented 82.12% of the estimated 'Tieton' genome.

Bud dormancy. Bud dormancy and ontogenetic development in sweet cherry buds were studied in Germany (Baldermann et al. 2018). The main phenolic compounds were caffeoylquinic acids, coumaroylquinic acids, catechins, quercetin and kaempferol derivatives. The results also supported the protective role of ascorbate and glutathione at the para- and endodormancy phases.

In Spain, Fadón et al. (2018) focused on the development of the flower bud in relation to dormancy and changes in the starch in the flower of two cherry cultivars. The flower buds remained during the win-

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ter at the same phenological stage, with flower primordia at the same developmental stage. However, an important variation in the starch content occurred in the ovary primordia cells.

The hormonal balance that fine-tunes the dormancy status in sweet cherry flower buds was studied in France (Vimont et al. 2018). The results demonstrated that the gibberellic acid pathways had distinct functions and could regulate dormancy in different ways. Following the observations that the abscisic acid levels are strongly linked with the dormancy depth, they successfully modelled the abscisic acid content and dormancy behaviour in three cultivars based on the expression of a small set of genes regulating levels of abscisic acid.

The recent French study evaluated the most important developmental phases of sweet cherry bud dormancy (Vimont et al. 2019). The buds in organogenesis, paradormancy, endodormancy and ecodormancy stages were defined via the expression of genes involved in specific pathways, and these were conserved among different sweet cherry cultivars. This work set the stage for the development of fast and cost-effective diagnostic tools to molecularly define the dormancy stages.

Physiological research. The profiles of the phenolic compounds and antioxidant properties of three Spanish and two other different sweet cherry cultivars were compared (Acero et al. 2018). The differences between the *in vitro* and in cell culture results provided evidence for the interaction among phenolic compounds of the extract.

The current season photoassimilate distribution (Ayala, Lang 2018) illustrated the dynamics of the ^{13}C contribution from each leaf population between vegetative and reproductive sinks during growth in orchards that provided useful physiological information for canopy pruning and crop load regulation.

The phenolic compound profile characterisation of sweet cherry cultivars (Ceccarelli et al. 2018) detected neochlorogenic and *p*-coumaroylquinic acids, (–)-epicatechin, quercetin 3-O-rutinoside, and cyanidin 3-O-rutinoside as the major compounds in all the included cultivars. The phenolic compounds and titratable acidity played an important role in determining the antioxidant activity.

The impact of climate change on sweet cherry frost damage was studied in Germany (Chmielewski et al. 2018). The frequency and strength of the frost were characterised by a high temporal and local variability. No significant increase in the frost frequency and frost damage during blossom was found at both sites studied. In Geisenheim, the predicted frost damage significantly decreased when compared to the middle of the 21st century.

Physiological research in Italy (Gonçalves et al. 2018b) concerning the coloured fraction in sweet cherries revealed the best activity against haemoglobin oxidation and haemolysis. The coloured extract exhibited the largest cytotoxic effects in Caco-2 cells, while the total extract was the most efficient in protecting these cells against the oxidative damage induced by *tert*-Butylhydroperoxid.

Metabolomic profiling during post-harvest responses of fruit and stem tissues was evaluated in Greece (Karagiannis et al. 2018). Marked tissue-specific differences were detected among the sweet cherries exposed to individual and combined 1-methylcyclopropene and modified atmosphere packing treatments, notably for amino acid biosynthesis.

The effect of stick sweet cherry extracts on biological activities in different bacteria (Maysoon, Saleem 2018) indicated the antimicrobial activity of the latter via inhibition of the growth of different types of pathogenic bacteria.

The metabolic mechanisms underpinning vegetative bud dormancy and shoot development were studied by Michailidis et al. (2018). Several amino acids and classes of secondary metabolites, including anthocyanidins, flavonoids, and lignin-related compounds, were altered during the developmental stages.

Bilbao-Sainz et al. (2019) examined the physical characteristics and nutritional values of thawed cherries frozen to −4 °C and −7 °C in an isochoric system and compared them with those of fresh cherries, thawed cherries that were individually quick frozen, and thawed cherries frozen to −4 °C or −7 °C in an isobaric system.

A study of the physiological basics of the sweet cherry cultivar productivity depending on the rootstocks, interstems, and plant density confirmed that the cherry cultivars reacted differently to the varying plant density depending on their growth habit. Thus, they required different planting schemes (Bondarenko 2019).

Beconcini et al. (2019) discovered that the extract from sweet cherries improved the resistance of endothelial cells to oxidative stress. Different nanoparticle systems were physico-chemically characterised, and the antioxidant gastrointestinal permeability was evaluated in a triple-cell co-cul-

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ture model (Caco-2/HT29-MTX/Raji B) that resembled the intestine.

Volatile metabolites, quality, and sensory parameters of the 'Ferrovia' sweet cherry cold stored in air or packed in high CO_2 modified atmospheres were also studied in Italy (Cozzolino et al. 2019). Their results showed that the sweet cherry cv. 'Ferrovia' was sensitive to CO_2 accumulation (over 20%) in a low oxygen (about 1%) modified atmosphere, as demonstrated by increased respiration rate, biosynthesis of fermentative volatile metabolites, and sensory perception of off-odours.

Measurements of the antioxidant activity of sweet cherry fruit, petioles and leaves infusions and extracts indicated that their extracts could be used as a valuable cosmetic raw material that had a strong antioxidant ability and, at the same time, did not adversely affect the useful properties of the washing gel (Dziadek et al. 2019b).

Another study of the content of phenolic compounds in the peel and flesh of sweet cherry stated that the high variability in the phenolic compounds among the cultivars could be useful for breeding and underlined the importance of germplasm conservation activities (Gao et al. 2019).

The physiological properties of 12 sweet cherry cultivars were recently studied in China (Jia et al. 2019). The anthocyanin and flavonol cyanidin-3-O-rutinoside patterns were found helpful for the varietal assignment of cherries and could represent a preliminary index for grouping similar cultivars and colours.

'Royal Dawn' cherries were extracted and presented rutin as the predominant phenolic compound, unlike most sweet cherry varieties (Iglesias-Carres et al. 2019). Ethanol was evaluated as a replacement solvent instead of methanol, but it enabled slower extraction rates, especially for anthocyanins.

Metabolic features underlying the response of sweet cherry fruit to post-harvest UV-C irradiation enhanced our understanding of UV-C's function in fruit biology (Michailidis et al. 2019a).

A molecular analysis of sweet cherry cultivars revealed that cultivars genotyped by using simple sequence repeats and further investigated via cluster analysis disclosed a homogeneous genetic constitution. This result differed from commercial consents (Muccillo et al. 2019).

An examination of the quality parameters for the discrimination of four sweet cherry cultivars confirmed that the combination of volatile compounds and conventional quality parameters provided a correct classification rate of 84.1%, and the combination of minerals and conventional quality parameters was 86.4%. The combination of minerals, conventional quality parameters, and sugars provided the highest correct classification rate of 88.6% (Papapetros et al. 2019).

Another study concerning the content of polyphenols and carotenoids in sweet cherry fruit cultivars found high variability in the phenolic and carotenoid profiles and in their antioxidant activity (Średnicka-Tober et al. 2019).

Determining the agrobiological and biochemical aspects of the sweet cherry scion/stock combinations established that the stock's variety, shape, and interaction affected grafted trees' development, productivity, and durability (Upadysheva et al. 2019).

An intraspecific discrimination study of wild cherry populations from northwestern Turkey led to the conclusion that the DNA barcode technique, usually applied for species identification, can also be used as a scientific tool for the detection of plant biodiversity at a population level (Ünsal et al. 2019).

The content of kernel oils in four sweet cherry cultivars was recently analysed by Aqil et al. (2020) in Morocco. Twelve fatty acids were identified in all the varieties, with linoleic and oleic fatty acids being the most abundant ones. β-sitosterol, campesterol and Δ^5-avenasterol were the major compounds in the sterols.

Fuentealba et al. (2020) examined sweet cherry fruits' cell wall and metabolite composition from two cultivars with contrasting susceptibility to surface pitting during storage. They found higher contents of the *p*-coumaric acid derivatives L-5-oxoproline and D-galactose in the susceptible 'Sweetheart' cherries.

The physicochemical characteristics and phenolic profile of twenty-three sweet cherry cultivars revealed that sweet cherries represent a supply of high-value bioactive compounds, and the cultivar greatly influences their quantity (Gonçalves et al. 2020).

The spatial heterogeneity of the flesh-cell osmotic potential affected the partitioning of the absorbed water, which was recently studied in Germany (Grimm et al. 2020). The cells in the vicinity of the vascular bundle had a more negative osmotic potential than the cells more distant from the bundle.

Karydas et al. (2020) proposed a model for estimating the antioxidant content and activity. Their optimised model included 24 input variables, resulting in a 6.74 root mean square error. Provided the soil profiles and other ancillary data are known before the

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cultivation season, the captured drone images in critical growth phases and contemporary weather data supported the site- and time-specific harvesting.

The sugar and phenolic diversity in the floral nectar of the sour cherry was defined. The most abundant sugars included fructose, glucose, and sucrose. In contrast, arabinose, rhamnose, maltose, isomaltose, trehalose, gentiobiose, turanose, panose, melezitose, maltotriose, isomaltotriose, as well as the sugar alcohols glycerol, erythritol, arabitol, galactitol, and mannitol were present as minor constituents (Akšić et al. 2019). The most abundant phenolic compound was rutin, followed by naringenin and chrysin. In contrast, the chemical compounds in the nectar were cultivar-dependent.

Mohammed et al. (2020) tested the antibiotic sensitivity to illustrate that erythromycin and amoxicillin had no influence on the pathogenic bacteria, and only trimethoprim affected the different strains of the microorganism, except *Staphylococcus aureus* and *Pseudomonas aeruginosa*. A difference in the inhibition zone for pathogenic bacteria was also observed.

Using chemical indices and gel permeation chromatography, the discrimination of two early and late ripening cherry cultivars was studied in Portugal (Safarzadeh et al. 2020). The cultivars 'Lambert' and 'Takdaneh' exhibited a reduction in the total sugar after 7 and 14 days past the harvest.

Calcium (Ca) physiology focuses on identifying the key determinants of the Ca content in the development of sweet cherry fruit (Winkler et al. 2020b). The fruit held in a low relative humidity environment contained more Ca per fruit and had a higher Ca/dry mass ratio compared with fruit held in high humidity.

The optimised supercritical carbon dioxide extraction of sweet cherry (*Prunus avium* L.) leaves led to the identification of fragmentation pathways of the seven main components in the extract (Zhang et al. 2020a). The carbohydrates and bioactive substances in the extracts obtained suggested the potential for using leaves in the food and medical industries.

Breeding programmes. The results of sweet cherry novelties bred in Greece were published in 2018 (Ganopoulos et al. 2018). Optimal hybrid clustering was achieved after the analysis included characteristics of significant economic importance, including fruit shape and size, growth habit, and days to blooming. Based on their results, new sweet cherry hybrids with the special characteristic of self-compatibility have been developed.

A principal component analysis and fuzzy comprehensive evaluation were applied to sweet cherry cultivars in China (Peng et al. 2018). The cultivar 'Red' had the highest comprehensive quality, which could be utilised as the raw material for future breeding. Furthermore, another nine top cherry cultivars were recommended for use in future breeding programmes.

Sweet cherry breeding worldwide has been analysed recently in France (Garcia 2019). The most important public breeding programmes in the 20^{th} century were located in Chile, China, and Spain. Breeders are supposed to review the major goals, methodologies, and perspectives with regard to new directions and the needs of changing supply chains and climatic conditions. Cherry production faces significant threats related to the consequences of global climate change (particularly global warming) or the emergence of new pests and diseases (such as the fly *Drosophila suzukii*). Hence, breeders must incorporate new traits into their selection schemes, on top of the traditional and unavoidable ones, such as productivity, fruit size and firmness, taste quality, etc. Thus, it might not be straightforward to find interesting alleles in the breeder's portfolios for traits of adaptability to biotic and abiotic stresses. For this reason, the preservation and characterisation of germplasm resources should be considered an urgent priority.

A Hungarian group collected results obtained in several countries, defining what kind of sweet cherries and the most important characteristics the final consumers prefer (Bujdosó et al. 2020). They defined the taste, followed by the fruit's skin colour, as the most important characteristics for cherry consumers. Sweet cherries were preferred, but not with a very sweet taste. The buyers also favoured a large fruit size, red colour, uniform fruit shape, and medium-long stalk (40.1–45.0 mm).

The effect of low-temperature storage on the sweet cherry pollen quality was studied in the USA (Özcan 2020). Pollen was stored at temperatures of 4 °C, –20 °C, and –80 °C for 12 months, and the viability and germinability were determined at three-month intervals. They concluded that the pollen quality of these cultivars can be preserved even at temperatures less than –20 °C.

Evaluation of cultivars. The characterisation and differentiation of the botanical and geographical origin of selected popular sweet cherry cultivars were investigated in Greece (Papapetros et al. 2018). They analysed the obtained data using a multivariate anal-

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ysis of variance and a linear discriminant analysis. The combination of volatile compounds, conventional properties, and minerals provided the best correct prediction rate of 97.4% for botanical differentiation.

The effects of two sweet cherry cultivars on the shelf life of an innovative bakery product were studied in Italy (De Pilli et al. 2019). They developed a model system to obtain an innovative bakery product with minimally processed fruit. They highlighted the importance of choosing the accurate cultivar based on the purpose and recommended different cultivars for fresh consumption or processing. The cultivars must be fully ripe in both cases to retain higher flesh firmness.

Newly assessed sweet cherry cultivars were released in Romania (Iurea et al. 2019a). The cultivars with the largest fruit size were 'Elaiași' and 'Croma', with a weight between 8.9 g and 9.4 g and a 25.2–26.6 mm diameter. These dimensions were significantly larger on average than the 'Van' fruit.

Sarusu et al. (2019) published an evaluation of sweet cherry cultivars that were introduced to Turkey. The 'Veysel' early cherry cultivar was found to be the most productive. The late cultivar 'N. De Meched' and mid-season cultivar 'Techlovan' were also found to be very efficient. In terms of fruit sizes, the early sweet cherry cultivar 'P. Bernard', mid-season cultivar 'Summit' and late season cultivar 'Ziraat' produced the largest fruit.

The genetic dissection of the bloom time in a low chilling sweet cherry using a multi-family quantitative trait loci approach was studied in Spain (Calle et al. 2020). Their study aimed to investigate this trait's genetic control via analysing multiple gene families. Those were derived from the low chilling and extra-early flowering local Spanish cultivar 'Cristobalina' and other cultivars with higher chilling requirements and medium to late bloom times.

The vulnerability of sweet cherry cultivars to spring frosts was evaluated in Bulgaria (Malchev, Savchovska 2020). The most damaged hybrids were El.28-21 (95.00%), 'Van' (91.89%) and 'Bing' (89.41%). The next group included 'Lapins' (85.98%) and 'Rosita' (83.33%). The larger intermediate group contained 'Kossara' (81.67%), 'Rozalina' (76.00%), 'Sunburst' (75.00%), 'Bigarreau Burlat' (69.11%) and 'Kuklenska belitza' (66.67%). The candidate-cultivar El.17-90 'Asparuh' and El.17-37 'Tzvetina' had the lowest frost damage values of 55.00% and 50.60%, respectively. The measurements were performed continuously from the bud swell (BBCH 51) to the petal fall (BBCH 67) stage with the temperature variation from –0.6 °C to –4.9 °C.

The frost resistance of the sweet cherry cultivar 'Turgenevka' on different rootstocks was evaluated in Russia (Ozherelieva 2020). This cultivar on the 82987 rootstock had the best potential for frost resistance during spring frosts.

The estimation of the daily carbon demand in two sweet cherry cultivars was studied in Germany (Penzel et al. 2020). In this study, the required leaf area per fruit of two sweet cherry cultivars, 'Bellise' and 'Regina', was estimated in 2018 and 2019, based on the measured and interpolated values of the fruit growth and respiration rates. The results can be applied to evaluate the tree crop load for precise management.

The discrimination of sweet cherry cultivars based on electronic tongue potentiometric fingerprints was studied in Portugal (Rodrigues et al. 2020). The electronic tongue could be used as a practical tool to discriminate among cherry cultivars. If applied by fruit traders, it can reduce the risk of mislabelling and increase consumers' confidence when purchasing this high-value product.

The effect of orchard covering systems on the fruit characteristics in fourteen sweet cherry cultivars was evaluated in the Czech Republic (Vávra 2020). The largest fruit size was recorded for the cultivar 'Tamara' with 29.5 mm, followed by the cultivar 'Horka' with 29 mm and 'Felicita' with 28.6 mm. The highest fruit firmness was recorded for the cultivars 'Amid' and 'Tamara' with an index of 77.5 and 73.2, respectively.

Harvest time. In Spain, the non-destructive determination of the optimum harvest time of the sweet cherry cultivar 'Cashmere' through CIELab colour coordinates and principal component analysis was studied (Lafuente et al. 2018). The study demonstrated that a simple colourimeter can be a suitable alternative to destructive methods to determine the optimum harvest time and can also allow the prediction of this commodity's shelf life.

An international research project in Australia, led by Hardner et al. (2019a), focused on predicting the genetic value for sweet cherry fruit maturity among environments using a 6K SNP array. The results found that genomic models could accurately predict the date of fruit maturity for untested individuals in new environments.

The application of melatonin as an inhibitor of ripening in sweet cherry orchard trees was studied in Spain (Tijero et al. 2019). The results could have

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important implications for the use of melatonin in controlling the timing of sweet cherry ripening.

Sarisu (2020) in Turkey studied interactions between the full bloom and harvest dates of 23 different sweet cherry varieties and their orchard air temperatures in 2006–2011. The variety 'Sunburst' was the most stable for flowering and harvest time at temperature changes among all the evaluated varieties.

Fruit quality. A report concerning the effect of abscisic acid (ABA) and methyl jasmonate (MeJA) pre-harvest applications on fruit quality was produced in Chile (Balbontín et al. 2018). Independent pre-harvest applications of ABA (0.1 mM), MeJA (0.4 mM), or both combined during two seasons at the fruit developmental stages of the fruit set or fruit colour change, significantly reduced the number of mature cracked fruit, even after a 6-hour-long immersion in water.

In Italy, Chiabrando and Giacalone (2018) evaluated factors affecting the fruit quality of fresh-cut sweet cherry. Their results confirmed that 'Giulietta' cultivar was suitable for use as a ready-to-eat product because its good firmness and titratable acidity were retained even after 10 days of storage.

Wan et al. (2018), in China, observed the effect of gibberellin on the fruit quality and anatomical structure. The application of gibberellins increased the single fruit weight and longitudinal diameter.

The impact of pre-harvest treatments with aminoethoxyvinylglycine on the fruit quality was studied in Turkey (Yildiz et al. 2018). This study revealed that these treatments were effective in delaying the softening of sweet cherry fruit. The main advantage was maintaining the firmness of the late-harvested fruit by retaining the fruit quality attributes.

The genetic control of fruit quality traits, particularly fruit firmness in the sweet cherry population, was recently examined in Spain (Balas et al. 2019). The cultivar 'Ambrunés' was used as a genetic source of these traits.

The fruit quality assessment of some sweet cherry cultivars was recently carried out in Romania (Iurea et al. 2019b). The highest fruit weight (7.5–8.9 g) was recorded for the cultivars 'Ludovan', 'Bucium', 'Ştefan', 'Iaşirom' and 'Golia'.

The applications of glycine betaine (GB) also affect the attributes of fruit quality and cause storage disorders in sweet cherries (Li et al. 2019). Three pre-harvest applications of 4 g/L GB displayed great potential in the improvement of quality attributes, reducing the susceptibility to storage disorders, and increasing the Ca concentrations in 'Regina' sweet cherries.

Correia et al. (2019) studied the effects of Ca and growth regulators on the sweet cherry quality and sensory attributes at harvest. Gibberellic acid and GB sprays were the best candidates to increase the quality attributes at harvest with two important commercial cherry cultivars.

The effects of different Ca salts and surfactants in sweet cherries were studied in Germany (Winkler, Knoche 2020). The results showed that spraying fruit with solutions of Ca salts increased the Ca mass per fruit. This increase resulted from the penetration of Ca through both the fruit skin and the pedicel-fruit junction.

The impact of integration of UV irradiation and chitosan coating on maintaining the post-harvest quality of sweet cherry fruit was reported (Abdipour et al. 2020). Their results indicated that integrated management was a potentially effective method for preventing undesirable post-harvest changes and extending shelf life.

Antognoni et al. (2020) published a paper on the fruit quality characterisation of new sweet cherry cultivars that they named a good source of bioactive phenolic compounds with antioxidant and neuroprotective potential. Their data suggested that the cherry extracts possessed neuroprotective activity *in vitro*. However, *in vivo* studies should be carried out to assess the real bioavailability.

Chemical flower thinning was applied in Poland to improve the fruit quality (Kurlus et al. 2020). The thinning resulted in larger and darker fruit comprising a higher content of total soluble solids and titratable acidity.

The application of GB to enhance the fruit quality was studied in the USA (Li et al. 2020b). The study aimed to evaluate whether the application of GB had the potential to improve the fruit quality of two sweet cherry cultivars. They evaluated the fruit firmness, size, skin colour, soluble solids content, titratable acidity and susceptibility to storage disorders (peduncle browning, pitting, and decay). They also determined that the frequency and timing of the application impacted the efficacy of the GB.

Xia et al. (2020) examined the influence of melatonin accumulation on the fruit quality and antioxidant properties. The results provided insights into the physiological and molecular mechanisms underlying the melatonin metabolism. The endogenous melatonin accumulated in young fruit and

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leaf tissues, and its content then decreased steadily toward maturation.

A fruit quality assessment system in sweet cherries was developed in China (Zhang et al. 2020b). The proposed quality assessment system provided complete and accurate microenvironment data and was used to further improve the quality and safety management of cherries during express logistics.

Anthocyanin concentrations. The optimised extraction of anthocyanins from the sweet cherry fruit cultivar 'Lapins' was investigated in Australia (Blackhall et al. 2018). The ultra-performance liquid chromatography-mass spectrometry (MS) analysis of the extract identified four anthocyanins, with cyanidin-3-rutinoside and peonidin-3-rutinoside accounting for over 95% of the anthocyanin concentrations. Cyanidin-3-glucoside and pelargonidin-3-rutinoside accounted for the remaining 5%. Under optimal extraction conditions, a total anthocyanin weight of 244 mg/100 g fresh cherries was found.

The effect of blue light on the anthocyanin accumulation in 'Satonishiki' and 'Napoleon' sweet cherry cultivars was studied in the USA (Arakawa et al. 2019). The efficiency of the blue light wavelength on the anthocyanin accumulation in 'Satonishiki' was examined using blue light at 430 nm to 490 nm. The wavelength of 450 nm was more effective than the other blue wavelengths. Blue light may play an important role in the development of the red colour in both cultivars under a tree canopy.

Health impact. The health benefits of sweet cherry consumption were determined in Portugal (Gonçalves et al. 2018a). The study aimed to present an overview of the phenolic composition and the methods used for identifying and quantifying these compounds, as well as report on their beneficial health properties, especially those related to antioxidant activity.

Kelley et al. (2018) summarised the results of human studies regarding the health benefits of sweet and tart cherries and products made from them. Most of these studies lasted less than 2 weeks and included serving the equivalent of 45 to 270 cherries/day in a single or a split dose. They found that the consumption of cherries positively affected oxidative stress, muscle soreness, blood pressure, arthritis, and quality of sleep. Their results also suggested that the consumption of sweet or tart cherries promoted health by preventing or decreasing oxidative stress and inflammation.

The health benefits of sweet cherry composition were also studied in Canada (Blando, Oomah 2019). Turkey, the USA, and Iran have been noted to have the highest sweet cherry consumption over the last 16 years. This research indicated that the consumption exerted beneficial health effects, counteracting oxidative stress, reducing inflammation, modulating blood glucose, and enhancing cognitive function.

A study in Poland (Dziadek et al. 2019a) investigated the effects of adding sweet cherry fruit to a high-fructose diet and lipid metabolism. The results showed that the addition of fruit reduced the adverse changes arising from the high-fructose diet.

The impact of sweet cherry fruit consumption on the consumer's health was also studied in Poland (Nizioł-Łukaszewska 2019). The addition of sweet cherry fruit extracts to the formulations resulted in a decrease in viscosity in comparison with the baseline sample. The highest drop in viscosity was monitored for the aqueous extract of the fruit.

The importance of fruit consumption for human health was studied in Germany (Winkler et al. 2019). A decrease in the incubation solution's osmotic potential decreased the rate of water uptake, further resulting in water loss to the solution. The "apparent" fruit water potential was consistently more negative throughout fruit development than the measured average osmotic potential.

Bioactive compounds with anti-ageing properties in sweet cherry fruit were studied in Spain (Agulló-Chazarra et al. 2020). After the analytical characterisation, a multistep screening approach, including antioxidant, enzymatic, and photoprotective cellular studies, was used to select the best extract for its benefits in the cosmetics industry.

The impact of climate conditions and spray treatments on health-promoting compounds in sweet cherry fruit was studied in Portugal (Correia et al. 2020a). The *Ascophyllum nodosum*, one of the novel spray treatments, appears to induce an effect opposite to gibberellic acid, increasing carotenoid and ascorbic acid, but lowering the phenolic content.

The foliar application of Ca and growth regulators in sweet cherries in Portugal (Correia et al. 2020b) confirmed that the general spray treatments improved the trees' physiological performance and water status. The biostimulant *Ascophyllum nodosum* and ABA were the best sprays, increasing the yield, reducing cherry cracking, and improving the photosynthetic performance and leaf metabolite content.

Researchers in Spain (Cruz-Carrión et al. 2020) discovered that the consumption of in-season sweet cherries, independently of their origin, promoted

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health by preventing oxidative stress, enhanced the antioxidant status, decreased alanine aminotransferase and aspartate aminotransferase activities, reduced the liver malondialdehyde levels, and maintained a constant blood serum.

Novel insights into the health-promoting properties of sweet cherries were presented in Italy (Faienza et al. 2020). The presence of natural polyphenolic compounds with high antioxidant potential drove and partly explained the beneficial effects. However, more translational and clinical studies should address this topic.

New technological approaches for recovering bioactive food constituents from sweet cherry pedicles were studied in Serbia (Nastić et al. 2020). The results pointed out that the sweet cherry pedicel extracts might be incorporated in formulations produced by the food and pharmaceutical industry.

Fruit cracking. Sweet cherry fruit cracking mechanisms and prevention strategies were reviewed in Portugal (Correia et al. 2018). New approaches to limit cracking, including the development of tolerant cultivars, mineral sprays, biostimulants and technologies for rainwater removal, such as orchard air-blast sprayers, as well as creating downwash by helicopters, were presented.

In China, effects of pre-harvest Ca sprays on the post-harvest disorders of late-maturing sweet cherry fruit were investigated (Dong et al. 2019). A single low concentration of gibberellic acid and Ca sprays enhanced the Ca uptake, cracking resistance, and fruit firmness without delaying maturation.

The influence of the plastic cover on the protection of sweet cherry fruit against cracking was studied in Poland (Mika et al. 2019). The plastic cover reduced the solar irradiation under the tunnel roof by around 40%. The light intensity within tree canopies was depleted by roughly 50%. However, it was reduced to 6% in the lower parts. This intensity is below a critical level of 20% estimated for apple trees.

The relationship between the fruit cracking susceptibility and changes in the osmolarity in cherry fruit flesh or skin was studied in France (Moing et al. 2019). Different levels of susceptibility to cracking were observed between the flesh and skin, revealing compositional gradients in fruit tissues.

The effect of a rain protective covering of a sweet cherry orchard was also recently evaluated in the Czech Republic (Suran et al. 2019). The rain protective covering of the cherry orchard was the most effective in eliminating the fruit cracking within the cultivars 'Burlat', 'Tamara', and 'Justyna'. Obviously, fruit cracking was affected by the weather conditions during the specific year.

A review from Germany (Winkler, Knoche 2019 on Ca and the physiology of sweet cherries focused on rain cracking. They discussed the effects of the pre-harvest and post-harvest applications of Ca that also improved the fruit firmness, decreased pedicel shrivelling and reduced the incidence of fruit rot.

The efficiency of pre-harvest Ca treatments against sweet cherry fruit cracking was studied in Portugal (Breia et al. 2020). In that study, they characterised, for the first time, the plasma membrane sweet cherry aquaporin's ability to transport water and H_2O_2 that was upregulated by the pre-harvest exogenous application of the $CaCl_2$ supplements.

The effects of a sprayed exogenous compound on sweet cherry fruit cracking were also studied in Portugal (Correia et al. 2020c). They found that, at the fruit-ripening stage, larger cell sizes of the epidermis, hypodermis, and parenchyma cells lower the cracking incidence. This finding indicated the importance of the flexibility and elasticity of the epidermis.

Very recently, sweet cherry fruit cracking has also been studied by testing methods and cultivar-metabolic screening in Greece (Michailidis et al. 2020b). This study brought insight on the cracking evaluation process in cherry fruits and provided novel information that can be used in the future for potential molecular breeding efforts focused on improving the sweet cherry fruit resistance to cracking.

The efficacy of cuticle supplement sprays on fruit cracking in the sweet cherry has also been studied within an international research project in the USA (Measham et al. 2020). The efficacy of anti-transpirant sprays on reducing fruit cracking in cherries was confirmed, and the impact on the fruit quality at harvest and during post-harvest storage was evaluated.

Fruit cracking in sweet cherry cultivars in correlation with the quality attributes was examined in Portugal (Pereira et al. 2020). The analysed quality parameters were influenced by the cultivar. The cv. 'Lapins' produced larger, heavier, firmer, and sweeter fruit, with more acidity and a higher maturation index.

Cherry fruit cracking was evaluated by Winkler et al. (2020a) in Germany. They compared the cracking of fruit submerged in water, the fruit remaining attached to the tree, but was exposed to a simulated rain, as well as detached fruit, placed in a wire cage and positioned in the canopy where it was exposed to a simulated rain. The cracking was primar-

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ily a function of the wetness duration and the area wetted. The longest length of time and the area wetted contributed the most to the cracking of the submerged fruit, followed by the attached and detached fruit exposed to the simulated rain.

Water influx through the wetted surface of the fruit in relation to rain-cracking was also examined in Germany (Winkler et al. 2020c). They demonstrated that a solute efflux occurred from the wetted fruit. The gravimetrically determined water uptake represented a net mass change, representing the influx minus the solute efflux.

The impact of the high tunnel cultivation of sweet cherries on the physiological and production variables was demonstrated with the use of high tunnels for 'Royal Dawn' on MaxMa 14 sweet cherry production in a Mediterranean-type climate. It reduced the susceptibility to rain-induced cracking, advanced the time of harvest, and increased the fruit size (Blanco et al. 2019b).

Storage quality. The failure of the antioxidant scavenging system in advanced ripening stages is one of the most important factors of fruit decay (Mirto et al. 2018). The accessions with high antioxidant metabolite contents exhibited low enzymatic activities. The observed differences were most likely due to the endogenous characteristics, making these accessions particularly interesting for breeding programmes aimed at the improvement of the fruit quality and shelf-life and for addressing the cultivation of a specific characterised cultivar based on the intended use, i.e. fresh consumption or processed products.

Orange peel storage fruit disorder of the sweet cherry was studied by Schlegel et al. (2018). They found no significant difference in the permeance of the skins or in the turgor of cells at the outer mesocarp between fruit without and with orange peel.

Michailidis et al. (2019b) studied factors underlying the post-harvest sweet cherry fruit senescence. Ca treatments somewhat delayed the fruit senescence as evidenced by changes in the fruit colour darkening, skin penetration force, and respiration activity.

The role of ethylene and 1-methylcyclopropene (1-MCP) in the early-season sweet cherry 'Burlat' storage life is known. Serradilla et al. (2019) demonstrated that continuous ethylene exposure reduced the accumulation of ABA, resulting in a higher weight and the loss of firmness. Moreover, the ethylene application decreased the titratable acidity throughout the storage, thus indicating an effect on the sweet cherry senescence.

The post-harvest UV-C treatment significantly extended the shelf-life of treated fruits (Pristijono et al. 2019). The post-harvest UV-C treatment has, under certain conditions, the potential to reduce the incidence of decay and maintain flesh firmness in fruit stored at an ambient temperature of 20 °C. However, no significant effect was observed when the fruit was stored at 1 °C.

The combination of an ultrasound and a salicylic acid treatment could be used for extending the shelf life of cherries during storage and enhancing the content of the bioactive compounds (Bal, Torçuk 2020).

The pre-harvest application of harpin β protein improved the fruit on-tree and storage quality attributes (Li et al. 2020a). The results revealed that 'Lapins' cherries had better quality attributes than the 'Early Bigi' counterparts. However, the latter were still very valuable to the region due to their early ripening.

Controlled atmosphere storage. The combined treatment of modified atmosphere packing with aminoethoxyglycine to maintain the sweet cherry quality throughout the cold storage and shelf life was studied in Turkey (Guler et al. 2019).

The effect of storing in a controlled atmosphere on the post-harvest quality and browning of sweet cherries was studied in China (Yang et al. 2019). The controlled atmosphere storage inhibited a reduction in the firmness of the fruit, and preserved the total soluble solid, titratable acidity, and ascorbic acid concentrations for longer, thus maintaining better fruit quality. The accumulation of membrane lipid peroxide malondialdehyde, and an increase in the relative permeability, were also significantly decreased.

The effect of the CO_2 concentration on the sweet cherry preservation in modified atmosphere packaging was also proven in China (Xing et al. 2020). The results demonstrated that the storage atmosphere treatments had a certain inhibitory effect on the deterioration of the sweet cherries. In particular, a 10% CO_2 content in the atmosphere reduced the rotting rate, maintained the firmness, delayed the change in soluble solids and vitamin C contents, and reduced the activity of polyphenol oxidase and peroxidase.

Tree training. The yield and fruit quality of the 'Regina' sweet cherry cultivar on five semi-dwarfing rootstocks in combination with Kym Green Bush or Vogel central leader training systems were studied by Long et al. (2018). The Vogel central leader was the most common training system for 'Regina'. However, a labour scarcity and increased labour costs cause growers to seek alternative training sys-

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tems that produce high yields of good quality fruit with improved labour efficiency.

Michailidis et al. (2020a) studied the impact of girdling on the metabolism in two sweet cherry cultivars. Both cultivars were girdled before full blossom. This process significantly altered the fruit ripening physiognomy and could induce long-term changes in the metabolism.

Rootstock impact. The physiological responses of cherry rootstocks to short-term salinity demonstrated that a higher tolerance to short-term salt stress was associated with a lower depression in the plant growth, a decrease in the chlorophyll content, and higher stability in the cell membranes as determined via the membrane permeability measurement (Aras, Eşitken 2018).

The same authors examined the response of sweet cherry trees grafted onto CAB-6P, MaxMa 14 and Mazzard rootstocks to short-term salinity (Aras, Eşitken 2019). They found a higher tolerance to short-term salt stress for cultivar '0900 Ziraat' grafted onto Mazzard and associated it with a lower depression in the plant growth, a smaller decrease in the chlorophyll content, and a higher stability in the cell membranes.

They also assessed the leaf characteristics, including the relative chlorophyll value, anthocyanin contents, stomatal conductance, leaf area, leaf relative water content value, and epicuticular content of six different cherry varieties grafted onto the MaxMa 14 rootstock (Aras, Keles 2019).

The rootstock effects on the vigour, production, and fruit quality in sweet cherry were studied by Balducci et al. (2019). They found no univocal combination between the scion and rootstock equally valid for all the considered parameters. The rootstock capable of ensuring good yields, as well as sensorial and nutritional quality, was Adara/Major. From the productive and qualitative point of view, GiselA 6 is well adapted to these conditions, while the MaxMa 14 rootstock stands out for nutritional quality, although it induces a high reduction in the vigour, poor vegetative renewal and low average fruit weight.

The results evaluating the impact of the rootstock on the fruit quality after short-term cold storage conditions in a high (20%) CO_2 content led to recommendations for preserving the fruit quality parameters, including a low decrease in firmness, preservation of the high soluble solid content/titratable acids ratio, minimisation of fungal infections, and keeping the green colour in the peduncle (Dziedzic, Błaszczyk 2019).

The impact of dwarfing and semi-vigorous rootstocks on canopy architectures, the fruit quality and yields of sweet cherries on improved orchard designs for the next generation of light- and labour-efficient canopy architectures enabled the formation of high-quality sweet cherry production systems across the range of rootstock vigour traits (Lang et al. 2019).

Long et al. (2019) revealed that sweet cherry orchard profitability depends on new rootstock and cultivar interactions. New scion and rootstock cultivar releases allowed growers to exceed the economic benchmark. In a rootstock trial, 'Bing' cherries on Krymsk 5 rootstock yielded 21.0 t/ha while Krymsk 6 yielded 21.7 t/ha (5^{th}–8^{th} leaf).

Different rootstocks (MaxMa 14, GiselA 5, GiselA 6 and SL 64) affected the quality properties and bioactive compounds of the '0900 Ziraat' sweet cherry fruit (Karakaya et al. 2020). The measured external qualities of fruit included differences in the fruit weight, thickness and length, firmness, chroma value, hue angle, and internal qualities, such as soluble solid content, acidity, vitamin C contents, and total phenolic and flavonoid compounds. The rootstocks had an impact on the content of the bioactive compounds and fruit quality.

Sweet cherry rootstocks influence the growth and productivity of cultivars (Tabakov et al. 2020). The rootstock GiselA 6 produced the largest cumulative yield and the highest productivity in terms of the trunk-cross-sectional area and crown volume among all the studied cultivars.

Irrigation impact. The impact of regulated deficit irrigation on the shelf life of sweet cherry fruit was studied in Spain (Blanco et al. 2019a). During post-harvest, significant differences were monitored in soil and plant water indicators such as the soil matric potential, midday stem water potential, and maximum daily branch shrinkage between control treatment and regulated deficit irrigation treatments.

A cooperative Turkish and Polish research project evaluated sweet cherry tree water requirements (Senyigi et al. 2019). Higher irrigation requirements in the province of Isparta in Turkey compared to the Polish region of Bydgoszcz resulted mainly from the smaller amount of precipitation and differences in the distribution of precipitation during the vegetative period.

Irrigation had an impact on the bioactive compounds in the sweet cherry fruits and their quality changes during shelf life (Martínez-Hernández et al. 2020). The phenolic compounds in the cherry skin

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decreased during storage. However, a UV-C treatment inhibited this reduction and even increased the total phenolic content by 21–36% after shelf life in fruit grown under regulated deficit irrigation.

Orchard protection. Post-harvest changes in the primary and secondary metabolites of sweet cherry cultivars were induced by *Monilinia laxa* (Kiprovski et al. 2018). The results led to the use of 3-feruloylquinic acid, flavonols, and anthocyanins as crucial participants in coping with the disease.

Tait et al. (2018) assessed the efficacy of the proof-of-concept matrix as a management tool in laboratory and semi-field conditions. The volatiles significantly modified the response of *D. suzukii* in controlled electrophysiology and orientation studies, resulting in a 46.7% mean oviposition reduction in controlled laboratory trials on five susceptible fruit types. The fruit on bushes exposed to predetermined numbers of *D. suzukii* displayed 50% to 76% reductions in fruit infestation and total eggs laid, respectively, in gum treatments. Up to 40% of the fruit on the untreated plants were targeted by *D. suzukii*, whereas less than 20% of the fruit on the treated bushes were targeted.

CONCLUSION

This review cites 137 reports from 25 countries published between 2018 and 2020. The article is thematically divided into 16 chapters: genetic research, bud dormancy, physiological research, breeding programmes, evaluation of cultivars, harvest time, fruit quality, anthocyanin content, health impact, fruit cracking, storage quality, controlled atmosphere storage, tree training, rootstock impact, irrigation impact, and orchard protection. The highest research interest was given to the physiological research with 31 items, and the lowest was for orchard protection with only one item. High research effort was given to the fruit quality represented by the fruit quality and fruit cracking themes, with 15 and 14 research publications, respectively. This review shows the shift in the research scope from simple testing techniques to physiology clarification of inner tree and fruit processes, leading to the production of fruits of increased quality. The research themes solving the pure agro-techniques of the sweet cherry have a decreasing tendency.

What should focus on in the next research? The genetics and physiology of the sweet cherry still show high scientific potential, especially in the search for new molecular markers, genes, and gene expression. The physiology of trees would be of interest due to clarifying their processes leading to abiotic stress resistance. Based on the studies provided above, the genetic potential of the present cultivars is exhausted, and the agro-techniques would not bring a sufficient increase in the fruit quality. The solution may be the breeding of new cultivars and genotypes resilient to biotic and abiotic stresses with increased fruit quality.

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